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Orbital Debris Mitigation Techniques:
Technical, Legal, and Economic Aspects

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Abstract: This special report is the result of a two-year effort by a large working group that conducted surveys of the industry and its customers, as well as financial supporters, to assess the current technical, legal, and economic aspects of orbital debris mitigation. Specific attention is given to currently available technology and regulatory options, which are not used in either the US or other spacefaring nations.

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Special Project Report

Orbital Debris Mitigation Techniques:

Technical, Economic, and Legal Aspects

**Prepared under the auspices of the
AIAA Standards Program and the
Technical Committee on the Legal Aspects of
Aeronautics and Astronautics**

Abstract

This AIAA Special Report addresses the minimization of the orbital debris hazard from an interdisciplinary perspective. It reviews a broad range of existing and proposed debris mitigation techniques and presents the results of an AIAA survey of industry and government. It discusses a number of important economic issues associated with orbital debris and provides a first-order economic assessment of the mitigation techniques. Finally, the report describes the existing regulatory framework and addresses several options for implementing those techniques, both nationally and internationally.

This report is not an AIAA Position Paper.

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Foreword

This study was initiated in May 1989 under the combined auspices of the AIAA Standards Program Orbital Debris Study Group and the Technical Committee on the Legal Aspects of Aeronautics and Astronautics. Significant contributions were also made through the Space Operations and Support Technical Committee. The primary charge to the Study Group was to make a preliminary assessment of the existing and planned orbital debris mitigation techniques in the civilian sector from an interdisciplinary perspective that would examine technical, economic, and legal/regulatory aspects. The purpose was to provide guidance to the AIAA Standards Program on the mitigation techniques most promising for technical standardization and to recommend national and international regulatory options.

The Study Group and its discipline panels held a series of meetings between May 1989 and November 1991, during which we received briefings by government representatives from the National Aeronautics & Space Administration, the Department of State, the Department of Transportation / Office of Commercial Space Transportation, and the Federal Communications Commission.

The Study Group's Technical Panel also conducted a survey of debris mitigation techniques currently in use or being considered by spacecraft manufacturers and operators, in both the civil government and private sectors. This survey and its tabulated results are given in Appendix A.

I would like to express sincere gratitude to all of the Study Group members and other individuals who contributed to this effort. In particular, thanks are due to James French, Claire Johnston, Nancy Ligos, and Harry Sheetz of AIAA Headquarters for encouragement and administrative support; Altoria Bell for secretarial services; and the following individuals who took the time to review this report: Jeff Anderson, Howard Baker, Walter Flury, Joel Greenberg, Larry Heacock, Dan Jacobs, Don Kessler, Joe Loftus Paul Maley, Barry Matsumori, Norman Metzger, Paul Mizera, Ray Nieder, Jack O'Brien, Andrew Potter, and Ronald Roehrich.

Paul F. Uhlir, Study Group Chairman

Participants

AIAA Orbital Debris Study Group

Steering Committee

Paul Uhlir, National Academy of Sciences, (Study Group Chairman, Economics Panel Chairman, and Legal Panel Co-Chair)
James Kaidy, Booz, Allen, & Hamilton, (Technical Panel Chairman)
Pamela Meredith, Space Conform, (Legal Panel Co-Chair)
Gerald Dittberner, Kaman Sciences Corp.
William English, Attorney
John Gantt, Attorney
Molly Macauley, Resources for the Future
Darren McKnight, Kaman Sciences Corp.

Study Participants

Paul Uhlir, National Academy of Sciences
Gerald Dittberner, Kaman Sciences Corp.
Stephen Doyle, Aerojet Propulsion Division
William English, Attorney
John Gantt, Attorney
James Kaidy, Booz, Allen, & Hamilton
Stephen Knowles, NAVSPASUR
Robert Ludwig, Condon & Forsyth
Molly Macauley, Resources for the Future
Darren McKnight, Kaman Sciences Corp.
Martin Menter, Attorney
Pamela Meredith, Space Conform
Satish Mohleji, Mitre Corp.
Sylvia Ospina, Comsat
Milton Smith, USAF
Jeanne Suchodolski, Townsend & Townsend

The Orbital Debris Study Group approved the document in November 1991.

The AIAA Standards Technical Council approved the document in January 1992.

Executive Summary

A scant 40 years ago, before the first launch of a man-made object into space, the idea of trash littering outer space as a result of human activities was difficult even to imagine. But trash in space, or more specifically, debris in Earth orbit, is no longer merely a conceptual problem. It is now the subject of intensive study and government policy-making, and a very real and growing threat to all space programs.

There are four general sources or classifications of orbital debris: discarded rocket bodies, inactive payloads, debris from the operation of spacecraft, and fragments caused by collisions or explosions. The mass, size, location, and distribution of this material varies over time and significant uncertainties remain in the accurate characterization of the problem, particularly with regard to debris that is smaller than 10 cm.

Despite these uncertainties, a general consensus has developed among space experts in all disciplines that in the absence of any efforts among the spacefaring nations to control the problem, orbital debris could severely restrict the use of some orbits within a few decades. All government reports and policy statements issued to date have consistently cited the need to minimize the growth of such debris, and the U. S. government has already made significant progress in researching and defining the problem.

In the view of the Study Group, what matters most about the orbital debris problem is not what we do not know, but what we do know. Although we may be relatively ignorant about the total number, size, and distribution of the debris, we know that it already poses a small, but growing threat of damage or destruction to our operational spacecraft. Although we may not know with certainty what the global launch rate will be in the coming years, we know that the hazard generally will continue to increase with every launch of a mission that does not prevent the creation of new pieces of debris. This report focuses on the most promising methods for minimizing that hazard from technical, economic, and legal perspectives.

TECHNICAL ASPECTS

As used in this report, "mitigation techniques" refer to a broad spectrum of debris minimization or reduction measures that may be implemented, either through hardware design or spacecraft operation. They include techniques for prevention of debris generation, spacecraft disposal or active removal, and protection of spacecraft through shielding or collision avoidance. Shielding and collision avoidance techniques are adaptive as well as mitigating; that is, they are used to improve spacecraft survivability in a worsening debris environment while also preventing the creation of more debris by protecting the spacecraft from collisions.

A comprehensive strategy for addressing the orbital debris problem requires consideration of both reactive adaptation measures and proactive mitigation techniques. This study focuses on the latter approach, however, because the Study Group considers this to be in more urgent need of attention.

The Study Group conducted a survey of industry and civil government agencies and organizations to obtain information on debris mitigation techniques as they relate to each debris class. For each class of debris, several specific mitigation techniques were provided as options. Survey respondents were asked to indicate which of the listed mitigation techniques they were already using or were considering for implementation. The following is a summary of the commonly practiced techniques and those favored by respondents for future implementation.

Some design and operational techniques already are being used with varying degrees of acceptance:

1) Discarded rocket bodies:
   * Expulsion of excess propellants and pressurants
   * Minimization of independent launch vehicle parts allowed to reach orbit
   * Securing parts to the upper stages
   * Use of the Collision Avoidance on Launch (COLA) program.

2) Spacecraft that have terminated their missions:
   * De-orbit and controlled reentry of low Earth orbit (LEO) spacecraft
   * Orbit maneuvering to shift spacecraft or components into disposal (graveyard) orbits (not a long-term solution).

3) Operational debris released from spacecraft during their missions:
   * Lanyards attached to all potentially releasable items such as camera lens and instrument covers, equipment used by astronauts in extravehicular activities, and other material
   * Structural attachment of otherwise detachable elements.

4) Fragments originating from explosions or collisions
   * Increased shielding

In addition to the above, other measures appear to have widely acknowledged potential. Among these are:

1) Discarded rocket bodies:
   * Use of separation devices
   * Use of the Computation of Miss Between Orbits (COMBO) program
   * Enhancement of the accuracy of the COLA program
   * Selection of launch times and dates to exploit natural forces for more rapid reentry of debris into the atmosphere.

2) Spacecraft that have terminated their missions:
   * Retrieval and/or reuse of spacecraft
   * Use of active beacons for spacecraft detection and avoidance.

3) Operational debris released from spacecraft during their missions:
   * Storing of trash and human waste, and return with logistics flights
   * De-orbiting trash and human waste for incineration in the atmosphere.

4) Fragments originating from explosions or collisions
   * Protecting and preventing hardware elements from exploding
   * Designing for graceful degradation of components and systems
   * Incorporating adequate shielding
   * Use of low fragmentation materials.

No formally adopted technical design or operations standards, guides, or even recommended practices currently exist for the mitigation of orbital debris. Nevertheless, the survey conducted through this study and supplemented by a review of the literature shows there are already a number of voluntarily adopted and widely practiced techniques. Although certain techniques are more commonly practiced than others, there is an increased awareness of the need to use them and a trend toward their continuation, both within the public and private sectors.

The very existence of these voluntarily adopted design and operational techniques for reducing the amount of artificial debris in Earth orbit leads to several conclusions. One is that both the government and the private sectors recognize that debris poses a potential hazard to operations in Earth's orbital environment. This is not a new finding in the context of government policies. Several recent government reports have focused on the problem and have strongly supported implementation of debris mitigation techniques. The finding is significant, however, in terms of private sector actions, because any design or operational practices in that sector have been developed voluntarily, rather than in response to any government regulations or agreements, indicating some level of corporate self interest.

Debris mitigation practices that have been adopted separately by two or more manufacturers or operators and that have been shown to be effective indicate the most promising areas to be pursued in the near future. This is especially the case for mitigation techniques practiced by the space agencies or companies of more than one nation. That a certain mitigation technique has been successfully used in the operational and commercial space environment provides a presumption in favor of its technical feasibility and cost effectiveness. This, in turn, makes such a technique a logical candidate for closer investigation as a potential industry or regulatory standard.

Nevertheless, no particular debris mitigation technique currently practiced by any portion of the industry provides a sufficiently compelling rationale for that technique to become an industry-wide standard without further investigation and analysis. A number of technical and economic tradeoffs still need to be considered.

The Study Group has identified four categories of debris mitigation measures that are the most promising candidates for near-term standardization, based on a preliminary technical assessment of the survey results and the current knowledge of the debris environment. These categories of techniques have been selected because of their demonstrated acceptance among a number of spacecraft manufacturers and operators, and because of their potential effectiveness in reducing the debris hazard.

1) Venting of residual fuel and pressurants from discarded rocket bodies. Debris from exploded rocket bodies (34 breakup events recorded as of 1991) accounts for over 1900 of the cataloged objects in Earth orbit. The venting of residual fuel and pressurants is a relatively simple and inexpensive technique already used in many U.S., European, Russian, and Japanese launches, but it has not been adopted by all launching government agencies or companies.

2) Boosting of satellites from geosynchronous Earth orbit (GEO) into disposal orbits. The satellite population in geosynchronous orbit is growing rapidly. The GEO is unique for communications purposes and for synoptic remote sensing observations, making it an important strategic and economic location. More GEO satellites have been deployed over the past decade than in all previous years combined, and the launch rate is expected to increase. There is no natural cleansing mechanism, such as atmospheric drag, so that any hardware deposited in GEO may remain indefinitely. A large number of GEO satellite operators in the U.S. and in other countries already use a variety of boosting techniques, some more effectively than others, near the end of useful life of their spacecraft. These techniques need to be evaluated fully from technical and economic standpoints so that a common approach with a minimum set of effective performance standards can be instituted.

3) De-orbiting spent hardware. The majority of all orbital debris consists of rocket bodies and payloads abandoned after their use. If left in space, this class of debris may provide a significant portion of the source material for a self-perpetuating sequence of collisions in the future. De-orbiting objects like these could significantly reduce the risk of collisions and the creation of hazardous fragmentation.

4) Reducing operational debris. Operational debris accounts for approximately 12 percent of all cataloged objects in Earth orbit. Operators of expendable launch vehicles, satellite, and piloted vehicles already have taken some corrective actions to reduce this type of debris. Their practices should be examined to determine the design penalties and cost tradeoffs in relation to their effectiveness in reducing harmful debris. The most beneficial designs should be recommended for universal use.

ECONOMIC ASPECTS

Improved understanding of the economic issues associated with orbital debris is essential to forming effective debris mitigation policies and regulatory frameworks. In addition, consideration of the economic impact of debris--on the public and private sectors in the U.S. and elsewhere--is important in assessing the political acceptability of any proposed solutions to the problem.

The growth of orbital debris, if left unchecked, will increasingly endanger many, if not most, of the activities we carry out in Earth orbit. The cost of all future activities is likely to increase over the long term, and may eventually make certain functions prohibitively expensive, or even physically impossible. ***It is essential for the United States to protect its long-term strategic, economic, and scientific interests in space and to preserve the ability to operate effectively in Earth orbit.***

A broad range of responses is possible, from the laissez-faire to the draconian. On the one hand, there are those who urge a cautious approach, preferring to study the problem further, to reduce the uncertainties that currently undermine accurate predictive capabilities, and to refrain from any actions that would have any negative economic consequences. Although an improved knowlege base might be expected to result in more efficient responses, the inherent risk in this approach is that if the problem turns out to be worse than anticipated, little will have been done to reduce its severity or to prepare ourselves to respond in a timely way.

On the other hand, those who believe that quick action is necessary to prevent or even to reduce the accumulation of debris in orbit, discount the importance of the scientific uncertainties; they focus instead on the growing sources of debris, which are well known. They consider immediate stabilization of the debris population and a "no net gain" policy to be the only responsible courses of action, given the difficulty in responding in a timely and effective manner once the problem has become obviously manifested. The inherent risk in this approach is that we may create greater economic dislocation now, with unnecessarily severe cost impacts, than if the scope and nature of the problem is better understood.

This situation, with a potentially serious problem identified, but with little immediate impact and an uncertain future, argues against an either-or policy. Instead, ***an appropriate balance needs to be achieved, one that supports low-cost and effective mitigation practices as insurance against a catastrophic situation, but does not unduly compromise either short- or long-range programmatic flexibility and economic growth. In order to avoid placing the U.S. space industry at a competitive disadvantage, mitigation techniques that are proposed for technical or regulatory standardization in the U.S. must also be pursued and adopted internationally, in most cases.***

In addition, the AIAA Study Group finds that the absence of a thorough analysis of the costs and economic considerations associated with the orbital debris problem severely undermines the capability to assess all options. A comprehensive economic analysis of orbital debris and its mitigation, sponsored by the relevant government agencies but performed by one or more independent organizations or contractors, is strongly recommended.

As mentioned above, the results of our technical survey demonstrate that effective design and operational debris mitigation practices are already used on a voluntary basis by a number of government and private sector parties. The voluntary adoption of debris mitigation practices in the operational environment suggests an acceptable cost-benefit ratio, and makes those practices currently in use appropriate near-term candidates for technical standardization and adoption on a wider scale, contingent upon proof of their effectiveness. The table below summarizes the preliminary technical and economic assessment of the most promising orbital debris mitigation techniques.

Preliminary Technical and Economic Assessment of Debris Mitigation Techniques

Mitigation Techniques (in priority order)	Debris Prevented	Technical* Implemen-tation	Cost*	Status
Venting residual fuel/pressurants from discarded rocket bodies	Large number, moderate mass	Simple	Low	Broad use in U.S., Europe, Japan, Russia; more planned
Boosting GEO satellites into disposal orbits	Small number, large mass (debris shifted, not removed)	Moderate	Moderate to high, depending on disposal orbit	Some use internation-ally; more planned
De-orbiting spent hardware at end of operational life	Small number, large mass	Moderate to difficult	Moderate to high	Very limited use; more planned
Reducing operational debris	Moderate number, small mass	Simple to moderate	Low to moderate	Some use; more planned

* Values assigned to technical implementation and cost are relative to each other, and may vary significantly by payload type.

LEGAL ASPECTS

The voluntary adoption of some design and operational techniques for reducing the growth of various categories of orbital debris may be seen as an encouraging development. It demonstrates that there are some technologically mature and economically feasible measures that can be readily applied in minimizing debris.

Although current industry initiatives are laudable, they are not sufficient. A well-organized and focused effort to implement effective debris mitigation techniques on a pervasive basis is necessary.

At this time, however, ***no technical standardization and only minimal legal regulation pertaining to the mitigation of orbital debris exists, either in the U.S. or internationally.***

Options for Incorporating Orbital Debris Mitigation Requirements into the U.S. Regulatory Framework

The principal finding of the 1989 Interagency Group *Report on Orbital Debris* was that additional information on the debris environment, its trends, and its implications was necessary for any consideration of policies, regulations, standards, or other actions. It was noted that without better knowledge of the environment, there was uncertainty about the urgency for action and the effectiveness of any particular mitigation measure.

Since the writing of that report, therefore, the focus has been on additional research. The government position was that once the appropriate agencies, mainly NASA and DoD, have better defined the debris environment, characterized the threats posed by the environment, and identified options for dealing with the threats, the Interagency Group would again begin to consider possible actions. At that point, the agencies with regulatory responsibilities and links to private industry would begin to look at cost-effectiveness issues and obtain input from commercial operators.

As a result of the progress made by some of the agencies in improving the understanding of the orbital debris problem since the 1989 report, the interagency consultative process was restarted in December 1991. Since then the Interagency Working Group on Orbital Debris (IWG-OD, as it is now called) has been reviewing the progress of the agencies over the past three years and planning the next series of actions.

The Study Group agrees with the government approach, in principle. In placing a greater emphasis on the long-term threat of the orbital debris problem, however, the Study Group finds that more could be done now to support low-cost and effective debris mitigation techniques as insurance against a potentially catastrophic situation.

The Study Group is encouraged that the previously limited coordination effort of NASA-DoD-DoT is now being expanded to include the relevant expertise and involvement of the other federal agencies that have a significant interest in space activities—notably NOAA, DoE, and FCC. The following activities should be strengthened or initiated under the leadership of the National Space Council, in addition to the program conducted up to now by NASA-DoD-DoT:

1) Significantly increase our capability to characterize accurately the orbital debris environment and to develop more realistic models to predict future trends.

2) Expand government-industry interaction already begun by NASA, with full involvement of the relevant engineering societies in developing common debris-reduction technologies, practices, and standards.

3) Allocate adequate resources for implementing the most cost-effective and operationally proven debris mitigation techniques on a voluntary, intdustry-wide basis in the near term.

4) Conduct intensive research on the most promising technologies that require further development, and thoroughly investigate all economic aspects related to the creation and minimization of orbital debris.

Given the continuing worsening of the orbital debris problem and the inevitable delays that would be experienced in confronting it only through voluntary action, however, ***careful consideration also should be given to accelerating the implementation of debris minimization measures through the judicious use of various national policy instruments, including incentives and regulations.*** Incentives can be used to encourage spacecraft manufacturers and operators to incorporate debris minimization techniques into their management and production plans. An effective method for introducing such incentives could be through the military and civilian procurement process, given the large number of spacecraft, launch vehicles, and space services procured by the government. Incentive instruments also might include monetary or other penalties on "dirty" technologies, financial inducements such as tax credits for "clean" technologies, and perhaps even orbital debris analogies to transferable emission rights (tradeable emission reductions, tradeable credits) such as those recently instituted under the Clean Air Act of 1990.

The use of incentives is generally preferable to regulatory action, because incentives are less obtrusive and can be used to influence decision-making within a market- or choice-based framework, rather than imposing a prescribed mode of conduct.

Nevertheless, selective use of regulatory mechanisms can help guide the recommended informal technical coordination process. Specifically, there are several actions that could be taken by the three agencies that have regulatory responsibility for the commercial sector.

The Study Group recommends that the Office of Commercial Space Transportation, the Federal Communications Commission, and the National Oceanic and Atmospheric Administration, in coordination with the other agencies, issue a Notice of Inquiry with regard to the suitability and desirability of imposing design and operational standards for minimizing the creation of orbital debris. Such a notice should provide suggested minimum standards for comment by all interested parties. Emphasis should be placed on debris mitigation techniques already in use by entities within each agency's regulatory scope. Adequate resources for carrying out these tasks should be specifically allocated.

These Notices of Inquiry would provide the space industry and other interested parties an opportunity to comment on the current orbital debris situation, and on existing industry mitigation practices and preferred future measures. The technical information gathered during this process would help the agencies consider appropriate rules or standards for minimizing the accumulation of orbital debris.

Options for Incorporating Orbital Debris Mitigation Requirements into the International Regulatory Framework

All activities in outer space are inherently international. Solutions to any problems created by those activities, including the mitigation and management of orbital debris, ultimately must be addressed on an international basis.

The options for addressing the problems associated with orbital debris on the international level may be divided according to **technical** and **legal** regulation.

Technical Coordination and Cooperation

The approach recommended by the Study Group for the U.S. to minimize the creation of orbital debris is suggested on an international basis as well. At a minimum, ***the same four initiatives recommended for implementation on the national level are likewise recommended for international action.***

NASA has already begun a program of technical consultations with the space agencies of other countries. Bilateral meetings have been held between NASA experts and space agency officials in Germany, France, Canada, ESA, the former Soviet Union, Japan, and China. ***The current government efforts need to be strengthened, however, and integrated into a well-structured process that:***

1) involves all launching states;

2) provides a sustained focus to the principal problem areas;

3) allocates adequate resources to resolving the highest priority problems; and

4) systematically transfers proven debris mitigation techniques and technology among all parties, subject

to legitimate national security and economic competitiveness concerns.

This intergovernmental technical coordination effort should be paralleled by vigorous cooperation in the private sector, through a process of citizen ("track-two") diplomacy. These steps are essential prerequisites for any subsequent--or parallel--negotiations to establish a formal agreement, as discussed below.

Development of Formal International Agreements

The development of a more formal structure for regulating orbital debris on an international basis can be comprehensively addressed either in the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), or in an ad hoc process independent of any established intergovernmental organization.

The U.N. COPUOS has already drafted five treaties and two important resolutions regulating space activities. Most nations are well aware of the problems of space debris and the issue has been raised at the United Nations General Assembly (UNGA) and at the COPUOS. Although the UNGA clearly has the authority to place orbital debris on the COPUOS agenda, it has not yet done so. There is an increasing interest within the COPUOS, however, to take up the orbital debris problem.

Rather than opposing COPUOS consideration of these issues, the United States could propose to the UNGA the "Amelioration of Orbital Debris" as an agenda item for the COPUOS and the creation of a special Working Group on Orbital Debris, first within the Scientific and Technical Subcommittee, and subsequently in the Legal Subcommittee.

Whether or not the orbital debris issue is taken up by the COPUOS, the United States should take the lead and invite all spacefaring nations, as well as public international spacecraft operating organizations, to participate in a conference to be held in a series of sessions. The first of these could be convened in the U.S. by the National Space Council in close consultation with the U.S. space agencies and the Department of State. The initial meeting could take place after the federal agencies have completed all the activities on their short-term agenda for orbital debris.

The first session would provide the opportunity for an open exchange of information and consensus building among interested parties, in a multilateral forum, regarding:

(1) common definition of technical and legal terms in the orbital debris context;

(2) orbital debris presently and potentially associated with national and multinational space programs; and

(3) spacecraft design and operating measures already practiced by some of the participants to reduce or mitigate the generation of debris, and that could be adopted by all nations involved in space activities.

At subsequent sessions, working groups could begin the formulation of standards for spacecraft design and operation, with the goal of minimizing the creation of orbital debris. The subsequent meetings also could determine the level of commitment the participating parties would be willing to make with respect to compliance with any formally adopted standards. This more formal process should integrate and build upon the technical coordination and cooperation activities recommended above.

1. INTRODUCTION

A number of government reports and policy statements have been published in recent years about the growing problem of artificial (man-made) debris in Earth's orbital environment.[1] As defined in this report, orbital debris consists of the physical by-products and material left in Earth's orbital environment during or following the operation of launch vehicles or spacecraft.

There are four general sources or classifications of orbital debris: discarded rocket bodies, inactive payloads, debris from the operation of spacecraft, and fragments caused by collisions or explosions. The mass, size, location, and distribution of this material varies over time and significant uncertainties remain in the accurate characterization of the problem, particularly with regard to debris that is smaller than 10 cm.

Despite these uncertainties, a general consensus has developed among space experts in all disciplines that in the absence of any efforts among the spacefaring nations to control the problem, "orbital debris could severely restrict the use of some orbits within a few decades." All government reports and policy statements issued to date have consistently cited the need to minimize the growth of such debris. The U. S. government has already made significant progress in researching and defining the problem.

The November 1989 Presidential Directive on the National Space Policy stated that:

> ...all space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. The United States government will encourage other space-faring nations to adopt policies and practices aimed at debris minimization.

The top three recommendations of the February 1989 *Report on Orbital Debris*, prepared by the Interagency Group (Space) for the National Security Council, elaborated on the National Space Policy as follows:

> A. Minimizing orbital debris should be a design consideration for all future commercial, civil and military launch vehicles, upper stages, satellites, space tests and missions.
>
> B. Each agency with operational or regulatory responsibilities for spacecraft should develop and distribute internal policy guidance consistent with National Space Policy regarding debris minimization.
>
> C. Current agency operational practices for debris mitigation during launch and space operations should be continued and, where feasible and cost-effective, improved.[3]

More recently, the FY 1991 National Aeronautics and Space Administration (NASA) Authorization Act included the following non-binding guidance:

> (b) Sense of Congress: It is the sense of Congress that the goal of the United States policy should be that
>
> > (1) the space related activities of the United States should be conducted in a manner that does not increase the amount of orbital debris; and
> >
> > (2) the United States should engage other spacefaring Nations to develop an agreement on the conduct of space activities that ensures that the amount of orbital debris is not increased.[4]

Other nations also have recognized the threat posed by orbital debris. For instance, the European Space Agency's (ESA) Space Debris Working Group reached the following conclusions in a November 1988 report entitled *Space Debris:*

> • Preventive Measures. Recognizing that space debris constitutes an unacceptable (man-made) risk to man and materials in space and on ground, the objective for the future must be to minimize the consequences of the existence of space debris and to minimize the creation of additional space debris.
>
> ...*immediate action* is required if irreversible developments or expensive consequences are to be avoided. The Agency is urged to undertake the necessary steps--organisational, technical and institutional--to contribute to countering this threat to space flight and to seek cooperation with other concerned parties.[5] [emphasis added]

The AIAA first addressed the issues concerning orbital debris in a July 1981 position paper, "Space Debris."[6] This study, chaired by Dr. Malcolm Wolfe of the Aerospace Corporation and conducted under the auspices of the AIAA Technical Committee on Space Systems, built upon the results of substantive studies initiated by NASA and the Department of Defense (DoD) in the late 1970s. At that time, the AIAA found the collision hazard posed by orbital debris to be "real but not severe."[7] The report concluded, however, that continuation of the existing design and operational practices and procedures would ensure that the probability of collision would increase and eventually reach unacceptable levels. The position paper recommended that the orbital debris issue should be addressed by all space users, and coordinated action taken promptly if the future use of space was not to be seriously restricted. It went on to recommend action in five major areas: education, technology, space vehicle design, operational procedures and practices, and national and international space policies and treaties.

It was not until the late 1980s, however, that the U.S. government and other spacefaring nations began changing official government policies, as indicated by the documents cited above. Some progress had been made over the past decade in organizing an orbital debris program in the U.S. and in focusing attention on specific aspects of the problem in a more coordinated manner, but much more remains to be done.

This study seeks to build on the past work of the AIAA in this area and to add to the ongoing research and discussion. Chapter 2 briefly defines the problem as it is currently understood and describes the four major categories of debris. Chapter 3 reviews a broad range of existing and proposed debris mitigation techniques, and presents the results of a survey of industry and government on these issues. Preliminary conclusions and recommendations are made regarding the most promising techniques. Chapter 4 discusses a number of important economic issues associated with orbital debris, and provides a first-order economic assessment of the mitigation techniques. The final chapter briefly describes the existing regulatory framework and addresses several options for implementing those techniques on national and international levels.

ENDNOTES

1. *See*, National Security Council Interagency Working Group (Space), *Report on Orbital Debris*, Washington, DC, February 1989, 53 p.; Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem*, U.S. Congress, OTA-BP-ISC-72, Washington, DC, September 1990, 52 p.; and Space Debris Working Group, *Space Debris*, European Space Agency, ESA SP-1109, November 1988, 71 p.
2. *Ibid.*, *Orbiting Debris: A Space Environmental Problem*, p. 3.
3. *Op. cit.*, n.1, *Report on Orbital Debris*, pp. 51-52.
4. FY 1991 NASA Authorization Act, P.L. 101-611, Section 118, "Space Debris" (1990).
5. *Op. cit.*, n.1, *Space Debris*, p. 69.
6. Wolfe, Malcolm, "Space Debris - An AIAA Position Paper," AIAA Technical Committee on Space Systems, July 1981, 6 p.
7. *Ibid.*, p. 1.

2. THE ORBITAL DEBRIS HAZARD

A scant 40 years ago, before the first launch of a man-made object into space, the idea of trash littering outer space as a result of human activities was difficult even to imagine. But trash in space, or more specifically, debris in Earth orbit, is no longer merely a conceptual problem. It is now the subject of intensive study and government policy-making, and a very real and growing threat to all space programs.

As indicated in Figure 2-1, orbital debris began to accumulate soon after the beginning of the space age, and has steadily increased. The periodic decline in the number of cataloged (observed and tracked) space objects is largely the result of increased solar activity, as discussed in the next chapter. At the end of 1991, the cataloged objects numbered over 7000, the preponderance of which were deposited in roughly equal amounts by the United States and the Soviet Union.

Figure 2-1 accounts only for those pieces that can be observed and tracked, however. Although these large pieces comprise the vast majority (over 99%) of the mass on orbit, there are many millions of very small pieces, or fragments estimated to be in orbit as well. NASA has estimated that there are between 35,000 and 150,000 pieces in the 1-10 cm range, and 3-40 million pieces under 1 cm.[1]

The current estimates of pieces under 10 cm in size are subject to large uncertainties because of inadequate observational capabilities. Nevertheless, several models have been generated that project the future debris environment based on assumptions of future launch traffic, future explosions or collisions, and future atmospheric density.

Figure 2-2 shows the results of one model projecting the growth in the number of cataloged pieces in Earth orbit between the years 1990 and 2010. An extrapolation based on past trends would roughly double the number of objects in orbit in 20 years. By adding anticipated launch rates to these projections, however, the amount of large debris objects may triple in that time. Other models have predicted even greater potential increases.

Although the cumulative growth in the number of debris pieces will also increase the probability of collision with an operational spacecraft, a greater worry over the longer term is the collision of debris with other debris, leading to a cascading effect of collision-induced breakups. The generation of orbital debris can result from continuing random collisions, which will produce additional fragments. It is hypothesized that this would increase the random collision rate.

Figure 2-3 shows the rate at which large objects may be expected to break up catastrophically as a result of random collisions. The collision rate will increase with higher launch rates and continued explosions of spacecraft (the causes of explosions are discussed later in this chapter). In the worst case scenario, an unstable, run-away environment of self-generating debris could result as early as the next century, if no steps are taken to address this problem.

It is also important to understand that problems caused by orbital debris are not uniform, and are dependent to a significant degree on the altitudes in which operational spacecraft and debris are located. The space around Earth may be divided into three orbital regions: low Earth orbit (LEO), geostationary or geosynchronous Earth orbit (GEO), and high Earth orbit (HEO). LEO generally is defined by objects orbiting the Earth at an altitude less than 2000 km. GEO is defined by objects orbiting the Earth at an altitude of approximately 35,786 km, which equates to an orbital period of approximately 24 hours. HEO is defined as the orbital region that is neither LEO nor GEO.

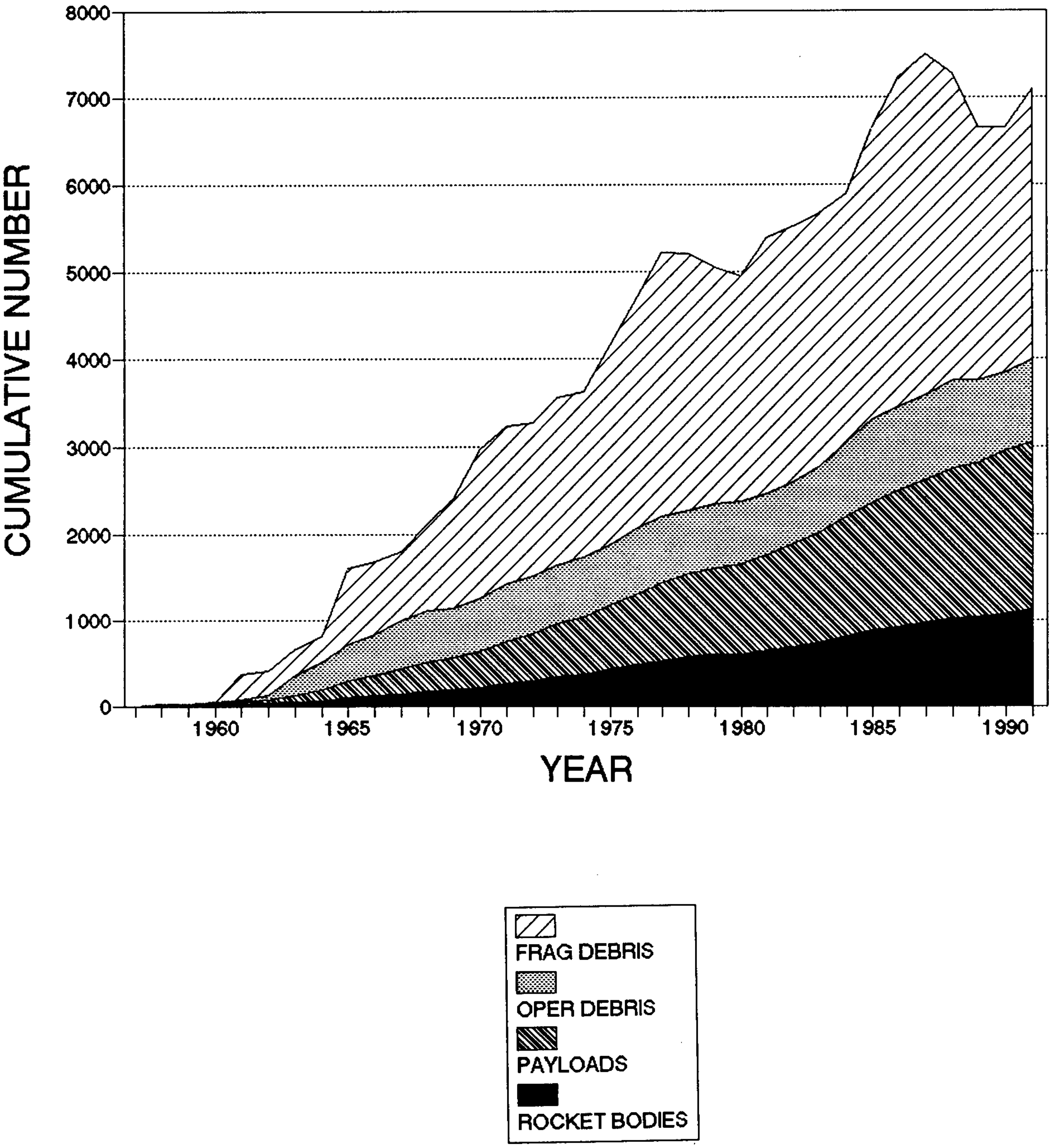

Figure 2-1 Number of Cataloged Space Objects in Orbit as of 27 September 1991
Source: Darren McKnight, Kaman Sciences Corporation, 1991.

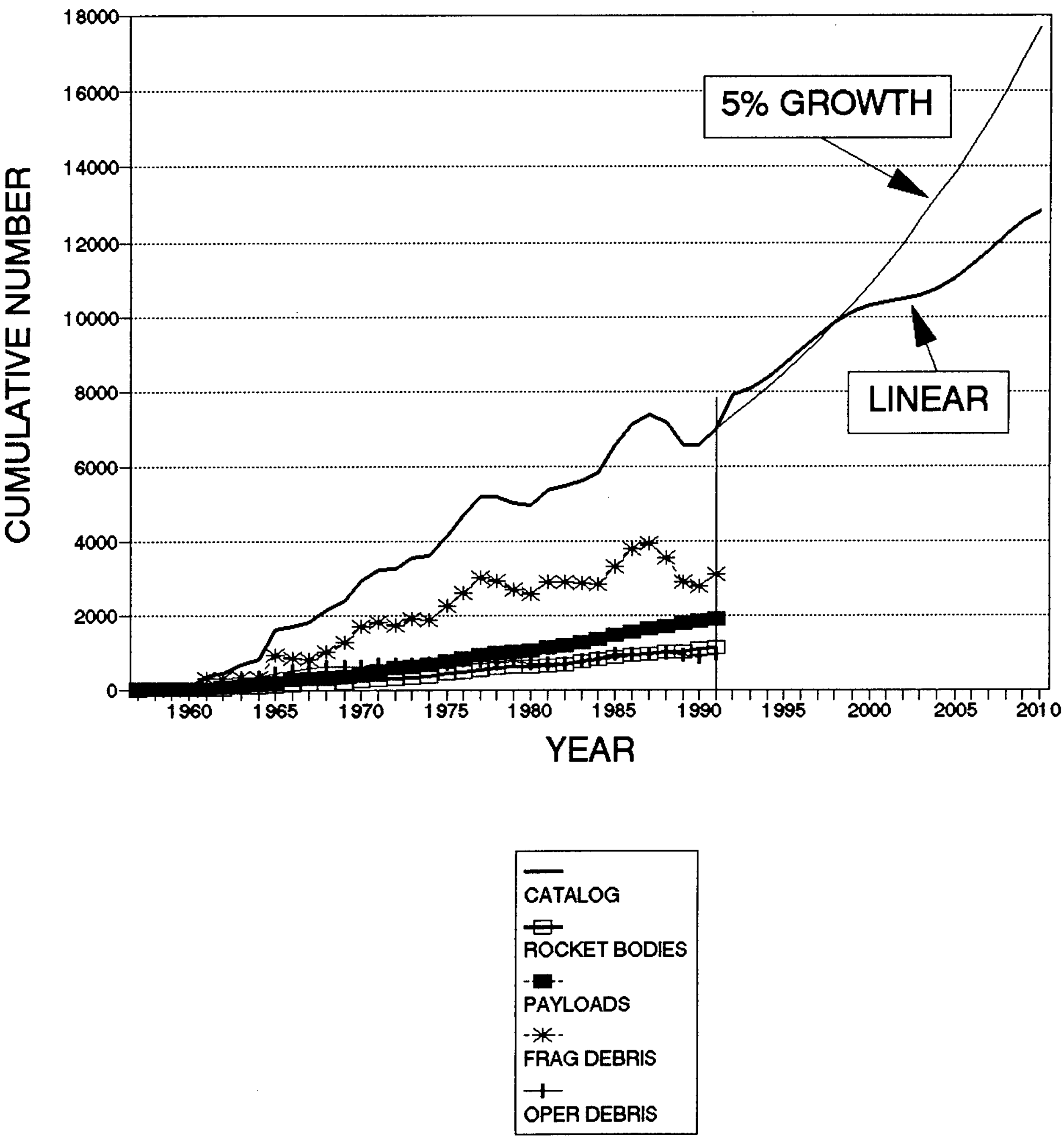

Figure 2-2 Projected Growth of Cataloged Debris (larger than 10 cm), 1990-2010
Source: Darren McKnight, Kaman Sciences Corporation, 1991.

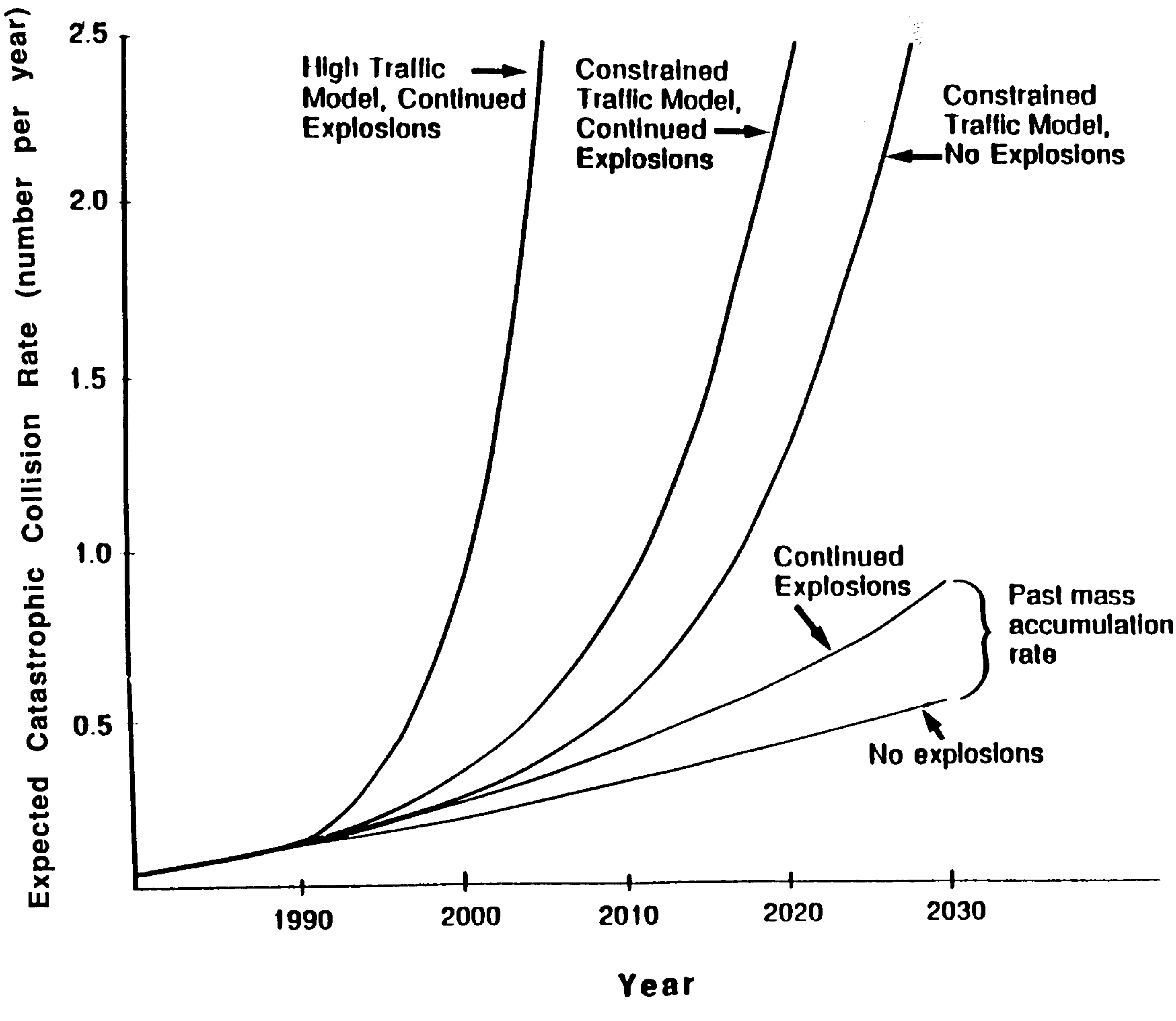

Figure 2-3 Rate that Payloads and Spent Rocket Stages Can Be Expected to Breakup Catastrophically as a Result of Random Collisions
Source: Donald Kessler, *Journal of Spacecraft and Rockets*, Vol. 28, No. 3, p. 347, May-June 1991.

Debris in LEO poses the greatest concern because most space missions, including all piloted spacecraft, operate at these altitudes. Also, about six out of seven pieces of tracked debris reside in LEO, although this may be a skewed number because objects are easier to detect at lower altitudes.

To date, debris in HEO has caused the least concern because there have been relatively few spacecraft that have used that orbital region, and consequently less than ten percent of the tracked objects may be found there. Because there is increasing use of HEO and because the lifetimes of objects in that region are extremely long, the problem of debris in HEO may soon take on added importance.

Finally, the GEO is well-known for its considerable economic value for providing a medium for satellite communications and synoptic environmental observations. According to the congressional Office of Technology Assessment report, *Orbiting Debris: A Space Environmental Problem*:

> GEO has a current population of almost 400 trackable objects, including about 100 active communications and other satellites. The exact quantity of objects in GEO is not known, because objects smaller than about 1 meter are currently untrackable at that distance from Earth. One analyst estimates that it may contain another possible 2,000 non-trackable objects. Objects placed in GEO will effectively remain there forever if not intentionally removed. Yet, because objects in this orbit all move in the same general direction (toward the east) at low velocities relative to each other, collisions between active, controlled satellites, and derelict spacecraft that wander about in the orbit would occur at moderately low relative velocities. As a result, experts estimate that the current hazard from orbital debris is less than the hazard from meteoroids passing through the orbit. Because of the lower velocities, chain reactions are less likely to occur than in LEO. However, as more active satellites are placed in this important orbit, and as greater numbers of uncontrolled, inactive satellites drift around in it, destructive collisions could become inevitable. Destructive collisions will also be more probable as inactive satellites that drift throughout the GEO band gain increasingly higher velocities as a result of small gravitational and other forces. At current densities for GEO debris and satellites, some analysts estimate that a large functioning satellite (30 - 50 meters square) will experience a 0.1 percent chance of being hit during its total operational lifetime.
>
> However, by the end of the century, if current trends for the number of satellites placed in GEO continue, that chance may increase dramatically to about 5 percent *per year* if no mitigating actions are initiated. If this estimate becomes reality, the typical satellite in GEO, which is expected to operate 10 years, would then experience a 40 percent chance of being struck by debris during its operational life.[2]

The disparate problems caused by orbital debris are virtually certain to get worse if nations continue to use the Earth orbital environment without any preventive measures. In fact, the only guarantee that the risk will not increase at some of the higher altitudes, perhaps to unacceptable levels, is to implement a "no net gain" policy for mass placed in orbit—a policy that would be economically prohibitive for the foreseeable future.

As indicated in Chapter 1, some spacefaring nations, including the U.S., have begun to recognize the potential severity of the problems created by debris left in Earth's orbit. They already have taken some measures to minimize both the mass placed in orbit as well as the number of pieces generated. They have also begun to adapt to the increasing risks posed by a degenerating environment, primarily by the use of added shielding to protect the most valuable space assets. The extra shielding planned for NASA's Space Station Freedom and the Canadian Radarsat missions are perhaps the best known examples.

Because it is highly unlikely that the global launch rate will significantly and permanently decline, or that all spacefaring nations will adopt a "no net gain" policy in the near term, the threat posed by an ever-increasing amount of orbital debris will have to be met by a mix of proactive mitigation techniques and reactive adaptation measures. This study focuses on the former approach, because the Study

Group considers this to be in more urgent need of attention.

DEBRIS CATEGORIES

For the purposes of properly assessing mitigation techniques, the sources of debris must first be categorized and defined. The four categories described below are consistent with those used by government space agencies, and include discarded rocket bodies, spacecraft that have terminated their missions (inactive payloads), pieces of hardware released from spacecraft during their operation, and fragments that have originated from explosions or collisions.[3]

1) Discarded upper stage rocket bodies

Vehicles in this category include both liquid- and solid-propellant stages that have partially or fully completed their missions. Such missions include boosting payloads to LEO, or from LEO to GEO, or to escape velocity. When in GEO, these vehicles pose a hypervelocity collision risk to any spacecraft orbiting below the apogee of the rocket stage, or above its perigee. Spent rocket stages also constitute a large reservoir of stored mass on orbit that may explode if they contain residual fuel or pressurants. Because of the specific nature and substantial potential impact of this class of debris, it is treated separately from the other debris categories, although certain characteristics may overlap.

2) Spacecraft that have terminated their missions (inactive payloads)

Mission termination entails the intentional shutdown of the spacecraft after the depletion of its propellant, loss of critical functions supporting its operation, or simply a programmatic decision to use new satellite capability. Although the subsequent motion of such a vehicle is to some extent predictable, once operational control of a spacecraft is lost, it generally poses a greater potential collision threat to others. Those in GEO begin to drift from their station-keeping positions, increasing their probability of colliding with other operational satellites. Both active and inactive satellites in LEO experience differential orbital precession, increasing the overall hypervelocity impact hazard and risk.

3) Pieces of hardware released (deliberately or due to failures) from spacecraft during their operation

The normal operation of a spacecraft may include the release of various parts such as camera lens or instrument covers, structural bolts, spent pyrotechnic devices, and other material. These objects pose a collision hazard to other spacecraft.

4) Fragments that have originated from explosions (accidental or induced) or collisions

As discussed above, the most populous component of the orbital debris environment consists of fragments from explosions or collisions that are dispersed into a broad range of orbits. The orbits of fragments from each breakup event may eventually precess to encompass the Earth. Fragments vary considerably in size, shape, and density depending on the cause of the breakup and structure of the satellite. Some fragments (generally with a diameter greater than 10 cm) are large enough to be tracked from ground-based radar, but the vast majority of them are too small to be characterized or cataloged adequately, which makes it very difficult to assess their actual population or location.

Figure 2-4 summarizes the sources of debris according to the object type, national origin, and hardware type, as well as the orbital distribution of debris.

In the view of the Study Group, what matters most about the orbital debris problem is not what we do not know, but what we do know. Although we may be relatively ignorant about the total number, size, and distribution of the debris, we know that it already poses a small, but growing threat of damage or destruction to our operational spacecraft. Although we may not know with certainty what the global launch rate will be in the coming years, we know that the hazard generally will continue to increase with every launch of a mission that does not prevent the creation of new pieces of debris. The remainder of this report focuses on the most promising methods for minimizing that hazard from technical, economic, and legal perspectives.

OBJECT TYPE	COUNTRY	HARDWARE TYPE	ORBIT
Fragmentation Debris 42%	USSR 47% (Intact 19%) (Debris 28%)	Originally Rocket Bodies 45% (Intact 17%) (Debris 28%)	LEO 75%
Nonoperational Payloads 23%	United States 45% (Intact 16%) (Debris 29%)	Originally Payloads 43% (Intact 29%) (Debris 14%)	GEO 19%
Spent Rocket Bodies 17%	Other 8%	Operational Debris 12%	HEO 6%
Operational Debris 12%			
Operational Satellites 6%			

Figure 2-4 Sources and Locations of Orbital Debris

Source: Darren McKnight, Kaman Sciences Corporation, 1991.

ENDNOTES

1. Kessler, Donald, vu-graph presentation on orbital debris, NASA Johnson Space Center, June 1991.
2. Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem*, U.S. Congress, OTA-BP-ISC-72, Washington, DC, pp. 16-17.
3. These categories are used by the European Space Agency, in its "Specification and Statement of Work, Safe Disposal of Orbiting Systems and Spacecraft - Including the Prevention of Hazardous Debris Creation," September 26, 1989. In addition, the report prepared for the U.S. National Security Council by the Interagency Group (Space), *Report on Orbital Debris*, February 1989, established a parallel set of four debris categories. These were operational debris, spent and intact rocket bodies, inactive (dead) payloads, and fragmentation debris.

3. TECHNICAL ASPECTS

This chapter presents the results of the Study Group's survey, and provides a preliminary assessment of design and operational practices that may be suitable candidates for technical standardization and adoption by all spacefaring nations. A review of the literature has provided additional relevant information.

SURVEY RESULTS

Description of Proposed Mitigation Techniques

The Study Group conducted a survey of industry and civil government agencies and organizations to obtain information on debris mitigation techniques as they relate to each debris class (see Appendix A). For each class of debris, several specific mitigation techniques were provided as options. As used in this report, mitigation techniques refer to a broad spectrum of debris minimization or reduction measures that may be implemented, either through hardware design or spacecraft operation. They include techniques for prevention of debris generation, spacecraft disposal or active removal, and protection of spacecraft through shielding or collision avoidance.[1] Shielding and collision avoidance techniques are adaptive as well as mitigating; that is, they are used to improve spacecraft survivability in a worsening debris environment while also preventing the creation of more debris by protecting the spacecraft from collisions. Survey respondents were asked to indicate which of the listed mitigation techniques they were already using or were considering for implementation.

1) Techniques for reduction of debris from spent rocket bodies

The survey listed six techniques for minimizing the growth of this class of debris:

(1) upper stage modifications to accelerate orbital decay and guarantee reentry;
(2) avoidance of explosions when reentry is not possible;
(3) modifications to expendable hardware for the reduction of excess operational debris;
(4) modifications to expendable hardware for disposal by atmospheric incineration;
(5) reduction of debris from propellants; and
(6) modifications to launch operations.

These techniques have also been recommended in several studies, as referenced below.

Separation maneuvers can be performed so that the upper stage vehicle executes a propulsive maneuver to reduce its orbital velocity, lowering its perigee to an altitude where atmospheric drag forces accelerate orbital decay and ensure reentry.[2] Another technique is the deployment of drag devices. These are structures deployed to increase the area extent of the upper stage, causing increased orbital drag and early decay for disposal in the atmosphere.[3] Inflatable devices can also be used to accelerate reentry and can decrease a vehicle's orbital lifetime from years to weeks.[4] These kinds of drag devices will only be effective for objects in orbital altitudes under 1000 km.

The design of upper stages that will remain in orbit for long periods of time can be modified to prevent a possible explosion by the expulsion of excess propellants and pressurants. Spent upper stage vehicles usually contain some residual propellants, which may overheat through exposure to the sun.[5] This may result in explosive expansion due to tank pressures that far exceed design limitations. Another problem can be caused by thermally induced expansion and failure of couplings and fuel lines, leading to an explosive reaction of the fuel and oxidizer. Similarly, pressurants and cryogenics in tanks may cause explosions if they are not vented.

Spacecraft can also be protected from spontaneous explosions of batteries through modifications that strengthen the battery casings, or by venting the gaseous byproducts of batteries.

Operational debris from upper stages can be reduced by modification of expendable hardware, decreasing the total number of parts allowed to reach orbit. This can be done by allowing fewer parts to separate from the vehicle before attaining orbital velocity, or by "bagging" to contain fragments from pyrotechnic devices. Another technique is to use lanyards or containment devices to secure parts that must separate after orbital velocity is achieved.

The reduction of discarded debris can be accomplished through operational disposal at low altitudes and velocities. Using separation devices earlier in the launch sequence ensures that the separated parts will not attain orbital speeds. Payload shrouds can be separated early enough in launch trajectories to ensure quick atmospheric reentry. The development of particle-free propellants may eliminate aluminum oxide particulates produced during solid rocket motor firings.

Pre-launch planning can reduce the risk of collision during the operation of a launch vehicle.[6] Data that provide the current and predicted trajectories of operational spacecraft as well as trackable debris, enable programs such as Collision Avoidance On Launch (COLA) and Computation of Miss Between Orbits (COMBO), used by the U.S. Space Command, to select safer launch times. At this time, however, support of the Space Command for non-military missions needs to be specifically requested and is provided only if their limited resources can be made available. Enhancements of these programs and the tracking data on which they are based could provide greater accuracy and possibly longer-range planning. Launch times and dates may also minimize debris by exploiting natural forces, such as periods of increased solar activity and solar-lunar gravitational perturbations. Solar activity, which varies approximately on an eleven-year cycle, energizes and expands the atmosphere when in its maximum phase. This causes atmospheric drag to affect orbital objects to a greater extent and at higher altitudes than during periods of lower solar activity. The orbital lifetime of objects is reduced by causing them to reenter sooner into the Earth's atmosphere.

2) Techniques for minimizing debris from spacecraft upon termination of their missions

Three general techniques have been identified for minimizing debris generation from spacecraft that have terminated their missions. These include: 1) LEO vehicle disposal; 2) high altitude and GEO vehicle disposal; and 3) facilitating avoidance by active spacecraft.

Disposal of LEO vehicles after they are no longer useful can be accomplished by de-orbiting them. A sufficient amount of propellant is required to perform an effective maneuver. A deployable or inflatable drag surface, previously mentioned as an upper stage disposal technique, may be used instead of, or in conjunction with, a de-orbit burn to accelerate reentry.

Retrieval and reuse of spacecraft could be an alternative to disposal by reentry. Although the NASA Space Shuttle has already been used for this purpose, this is generally not considered a practical near-term option, because of the high costs and added risks.

Higher altitude and GEO disposal can be accomplished through several techniques. Orbital maneuvering commands can be transmitted to a GEO spacecraft that has an operational maneuvering system to transfer it into a graveyard orbit, boosting the retired spacecraft above the geosynchronous orbit. In the long run, however, this would create another debris band only a few hundred kilometers away from GEO. Another technique, more effective, but much more expensive, is to boost the vehicle with a sufficient change in velocity (delta-V) to escape Earth orbit completely.

The use of active and passive debris detection and avoidance techniques has been suggested.[7] Active collision avoidance techniques include the use of a beacon which would radiate from out-of-service spacecraft in the visible, infrared, or radio portions of the spectrum to allow detection by passive sensors and thereby enable avoidance maneuvers. A passive laser-illuminated, or solar-illuminated, reflective apparatus on nonfunctional spacecraft also may be used to facilitate detection by an operational spacecraft. This approach would eliminate the need for a power system on the inactive spacecraft.

3) Techniques for minimizing debris released during the operation of spacecraft

Pieces of hardware that are released from spacecraft during their missions, either deliberately or due to non-catastrophic failures, constitute a debris class which lends itself to two methods of mitigation. Operational hardware may be retained within the spacecraft environment, and non-polluting waste disposal techniques from piloted vehicles may be used.

Techniques for retaining operational hardware within the spacecraft environment are similar to those mentioned with regard to the spent upper stage debris category. Various releasable devices, such as camera lens covers and instrument covers can be retained with lanyards. Bolts and shrouds can also be retained by enclosures or structural attachments.

Effective waste disposal techniques include storage for eventual return to Earth of items such as trash, biological waste, and residues from experiments. Destructive deorbiting (i.e., material vaporization upon atmospheric reentry) of these waste items also has been used.

4) Techniques for minimizing the creation of fragments caused by collisions or explosions

The severity of breakups in orbit may be mitigated by selectively strengthening structural elements and by designing safeguards to reduce the chance of explosion after termination of spacecraft operations. Components can be designed for graceful degradation by accounting for extreme thermal cycles after power and thermal control systems are no longer operational. Additional methods include "safing" the vehicle before deactivation by firing remaining ordnance onboard, and venting propellants and pressurants. Of course, the venting of explosive substances from rocket bodies, as discussed in subsection 1) above, is relevant here as well.

Spacecraft can also be designed to minimize the creation of debris in the event that a collision or explosion does occur. Such designs include dedicated debris shielding, the placement of potentially explosive or mission-critical components deep within the spacecraft surrounded by less critical protective elements, and the use of materials that produce few fragments.[8] Also, the miniaturization of spacecraft and subsystem parts may reduce the vehicle cross-section, and thus its chances of being hit. Passive shielding of spacecraft has been suggested for use on long-term missions.[9]

Analysis of Survey Responses

Spacecraft manufacturers and operators may contribute to various classes of debris, but not necessarily to all of them. The distribution of respondent categories must be understood to interpret the survey results properly. Therefore, the totals presented in this report have a relative significance only within each category. No single survey category could have an overwhelmingly affirmative response since most of the organizations responded only to certain parts of the survey. It also should be pointed out that many of the key players did not respond to the survey and are not represented in the results.

Respondents were divided according to manufacturers and operators, and these organizations fell into several subgroupings, which included an emphasis on launch vehicles, rocket stages, LEO and GEO spacecraft, and Space Station Freedom. Launch vehicle manufacturer and operator respondents included General Dynamics, Martin Marietta, and NASA-Goddard Space Flight Center/

and NASA-Goddard Space Flight Center/ McDonnell-Douglas. Responses regarding satellite development came from Ford Aerospace (now Loral Space Systems) and Ball Aerospace, while responses regarding spacecraft operation came from Intelsat, Comsat, the National Oceanic and Atmospheric Administration (NOAA), the European Space Agency (ESA), and Messerschmitt-Boelkow-Blohm (MBB/ERNO). A third category, upper stage development and operations, included contributions from Morton-Thiokol (now Thiokol), TRW, and Ball Aerospace. Finally, debris mitigation information on Space Station Freedom was provided by Boeing Aerospace and the NASA Marshall Space Flight Center. Table 3-1 summarizes this information.

Respondent Categories

Hardware Type/Potential Source of Debris	Developer	Operator
Launch Vehicles	McDonnell-Douglas ESA General Dynamics Martin-Marietta	NASA/Goddard Center ESA General Dynamics
Upper Stages	ESA MBB/ERNO Thiokol TRW Ball Aerospace	ESA MBB/ERNO
LEO & GEO Spacecraft	Ford Aerospace (now Loral Space Systems) Ball Aerospace ESA MBB/ERNO	Intelsat Comsat ESA MBB/ERNO NOAA
Space Station Freedom	Boeing Aerospace	NASA/Marshall Center

Table 3-1 Summary of Survey Responses by Category

Respondents were requested to indicate whether their respective organizations have already taken the measures listed on the survey, or if they planned to do so eventually. In addition, they were asked to expand on their answers whenever possible and to add to the list if the survey did not include all applicable mitigation techniques. Statistical results from the survey are presented in Appendix A.

These data indicate a clear, common trend toward certain mitigation techniques that are either being used now or are intended for future implementation. An analysis of the survey results follows, including specific applications provided by several respondents, as well as technical problems encountered in the implementation of these techniques.

1) Techniques for minimizing debris from spent rocket bodies

The most commonly practiced techniques in this category are upper stage modifications to avoid on-orbit explosions. In particular, the expulsion of excess propellants and pressurants is widely practiced.

The Ariane-4 H10 upper-stage propellant currently is vented for sun-synchronous delivery orbits, but not for upper stages in a geostationary transfer orbit (GTO).[10] This option, as well as a de-orbit maneuver option for the Ariane-5 L7 upper stage, are being considered. Further assessment of the performance tradeoff between propellant balance in the upper stage and operational lifetime of the payload is required.[11]

In the U.S., General Dynamics has practiced expulsion of all remaining propellants, including liquid hydrogen (H_2), liquid oxygen (O_2), hydrazine (N_2H_4), and water from Atlas/Centaur and Titan/Centaur upper stages.[12] All pressurants are released in the same manner while the upper stage is maintained in a benign condition until battery power is depleted. The Delta launch system is treated similarly, as noted in the response from Goddard Space Flight Center.[13] These techniques may be presumed to continue even though the responses do not so indicate.

Respondents also favored launch planning techniques that minimize potential collisions. Although Delta launch vehicle operators have used the Collision Avoidance On Launch (COLA) program,[14] seven respondents indicated that they plan to use it in the future. Nevertheless, this is not a technique that provides a high level of safety. Other launch planning techniques have been considered, including the use of the Computation of Miss Between Orbits (COMBO) program, but these are also not particularly effective because they do not include untrackable objects.

ESA continues to investigate these techniques and has found that collision avoidance maneuvers could improve spacecraft survivability.[15] The Agency has also found, however, that the major problem is not necessarily the mathematical formulation of the predicted trajectory, but instead, the orbital accuracy with which the trackable objects are known. This is due to the lack of sufficiently accurate observations by radar and tracking sensors and uncertainty in debris object shape, size, and weight. ESA has indicated that it uses optimization of launch times and dates to exploit the effect of the solar-lunar perturbations as a potential measure. For GTO trajectories, however, this technique may conflict with other launch window requirements, such as thermal constraints and attitude constraints for upper stage firing.

Another debris mitigation practice with some degree of acceptance is the reduction of excess operational debris through modifications to releasable hardware. The Delta[16] and the Centaur[17] expendable launch vehicles have used stage separation device containment. Modifications are planned for Thiokol's upper stages with the understanding that they will reduce the performance of the stage and its payload capacity.[18]

Results indicate low acceptance of upper stage modifications to guarantee reentry or acceleration of decay into the atmosphere. Separation maneuvers are most favored in this category, while drag devices are not widely accepted as potential measures at this time.

A potential area for improvement is in the reduction of upper-stage expendable hardware through disposal and reentry. The reduction of debris from fuel is the area that received the least amount of positive responses. Particle-free propellants are under development by Thiokol to eliminate both hydrogen chloride (HCl) and aluminum oxide (Al_2O_3).[19] At this time, however, the elimination of Al_2O_3 incurs a large performance penalty.

2) Techniques for minimizing debris produced by spacecraft upon termination of their missions

Of the three principal mitigation techniques identified in this debris category, two methods of vehicle disposal have been and will continue to be practiced. Disposal of both LEO and GEO spacecraft at the end of their missions has been identified as a current and future technique.

Specifically, the de-orbiting of LEO vehicles has been performed by Arianespace with an MBB/ERNO payload on the Ariane-4 [20] and by NASA with the Space Shuttle External Tank.[21] NASA is designing the Earth Observing System (EOS) satellites to have a controlled reentry capability as well.[22] Space Station Freedom (SSF) elements are being designed to be returned with the Space Shuttle.[23] However, NASA has not yet developed a comprehensive plan for disposing of the entire SSF at the end of its operational lifetime.

The former Soviet Union has been the only nation that has launched nuclear-powered spacecraft into Earth orbit over the past two decades. The Soviets have employed a technique of separating the nuclear power sources (U235 nuclear reactors, and radioisotope thermoelectric generators - RTGs) from the spacecraft prior to the spacecraft's reentry into the atmosphere, and boosting the reactor cores to higher orbits of approximately 1000 km altitude. Although the use of this technique seeks to minimize the risks posed by contamination of the atmosphere and surface of the Earth by nuclear radiation, it does not solve the long-term problem posed by the reactor cores as a debris source and a potential collision hazard. Such a collision would pollute an enormous volume of space.

Other potential LEO disposal techniques have received some preliminary consideration. Retrieval or reuse of spacecraft may be promising in the longer term. One Thiokol concept specifically calls for the use of high-impulse electric propulsion systems to boost all retrievables to a common collection point and to deploy a device to gather them.[24] Deployment of inflatable drag devices on LEO spacecraft to hasten reentry into the atmosphere at the end of useful life is a technique that is being considered by several organizations.

Disposal of spacecraft from GEO into higher graveyard orbits has already been widely used among GEO satellite manufacturers and operators. While implementation of this technique is varied, its purpose is the same: removal of the deactivated spacecraft from the immediate operational environment.

Manufacturers of GEO spacecraft have developed disposal scenarios and ascertained propellant required for boosting. Ford Aerospace (Space Systems/Loral) has studied the effect of GEO satellite boost and orbital plane drift from the equatorial plane over time.[25] Their analysis has shown that satellites tend to drift because of natural forces. Over a period of 54 years, a maximum inclination difference of 15 degrees will develop as the orbit precesses through the equatorial plane.

Without full coordination among all the operators of the retired spacecraft, however, the probability of collision increases in the disposal orbit as more satellites are boosted there. A partially successful disposal maneuver in fact may be worse than none at all.

ESA's policy requires GEO spacecraft to be inserted into a graveyard orbit above the geostationary ring at the end of their missions.[26] ESA officials believe this is currently the only practical measure to reduce the collision risk in GEO over the long term. In their opinion, such a measure must be applied by all major users of the geostationary ring, and the disposal orbit must be sufficiently high above GEO to avoid subsequent collisions.

The policy of the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) is to boost its Geostationary Operational Environmental Spacecraft (GOES) at the end of their useful lives, through a series of Hohmann transfers, into a circular orbit, 250 to 300 kilometers above the geosynchronous altitude.[27] By calculating when the minimum required amount of thruster propellant will be reached, NOAA/ NESDIS spacecraft operators can plan and execute these maneuvers. The propellant quantity cannot be measured using conventional propellant sensors because they are not accurate at low tank pressures. The agency uses the initial propellant reported at the launch site loading to begin propellant accounting.

Three methods are used to determine remaining propellant: (1) the use of propellant tank manufacturer specifications and ground test data; (2) real-time temperature and pressure data; and (3) propellant consumed during operational firings. Best efforts are made to leave approximately 2 kg of propellant. A three-step boost sequence then uses up the remaining propellant to boost the spacecraft at the northern- and southern-most points until all the propellant is depleted.

In using this procedure, the orbit is raised to the highest possible point no matter when the propellant is depleted because the perigee will be north or south of the geostationary arc, thus minimizing the possibility of collision. As a result of inaccuracies in propellant bookkeeping, however, NOAA/NESDIS has been able to exercise this technique with only three out of five spacecraft. In the other two instances, the fuel on the spacecraft was depleted before the technique could be implemented.

In the past, Intelsat has also shifted satellites into graveyard orbits.[28] Intelsat prefers to raise the orbit by 150 km above GEO, which is considerably less than the 250- to 300-km boost by NOAA/NESDIS. The first satellite was boosted above GEO in 1977 and 16 more have been boosted since then. Propellant accounting techniques have always been crucial to the success of this operation and previous techniques were not necessarily accurate. In the Intelsat-IV series of 12 satellites, attempts to estimate remaining propellant resulted in underestimation by an average of 2.3 kg per system. The Intelsat-IV and -V series used hydrazine for propulsion and control while later series--Intelsat-VI, -VII, and -K--use a bipropellant propulsion system for apogee raising and control.

For the Intelsat-IV series, the organization used new procedures to achieve greater accuracy in estimating propellant depletion. This was done by using redundant propellant systems. Late in the useful life of the satellite, with a substantial amount of propellant remaining (about 20 kg in each system), a valve was opened between the two propellant tanks, allowing the pressures to equalize. From that point on, only one system was used until empty. Careful monitoring during this process allowed operators to predict propellant use and depletion of the second system more accurately. Nominal position control, in both north-south and east-west directions, was performed until near the end of the design life of the spacecraft. At that point only the east-west position was controlled. Propellants were used at about one-tenth of the rate required for north-south station keeping, causing the satellite orbital plane to drift away from the equatorial plane. At the appropriate propellant lower limit, the boost was performed and in the process, all tanks, propellant lines, and pressurants were emptied, squibs fired and contained, and subsystems, including the radio frequency system, shut down.

Comsat voluntarily boosts its satellites above GEO and first performed such a maneuver with the COMSTAR (D-1) in 1984.[29] Since then, this maneuver has been applied to two other satellites. Raising the orbit to 150 km above GEO consumes about 1 percent of the propellant loaded at launch. Previous propellant accounting methods used by Comsat were subject to errors as large as 5 percent. The organization operates near end-of-life spacecraft in low propellant consumption, inclined orbits, and employs the "Comsat Maneuver." This method involves testing in orbit to compute the propellant remaining onboard to predict the time of end-of-life more accurately. Comsat derives the maximum revenue while ensuring an adequate propellant reserve for orbit boosting. Several thruster firings are used to boost the spacecraft out of GEO and to exhaust the remaining propellant. Pressurants are then vented and all subsystems are turned off.

While one affirmative response was received from Ball Aerospace for the possibility of providing a delta-V capability for escape from Earth orbit, Thiokol noted that this would result in a high performance penalty.[30] A concept put forth by Thiokol for implementation in the more distant future suggests the use of an electric propulsion system that would bring spacecraft back to a LEO space station for repair, refuel, reconfiguration, and reboost instead of disposal. This possibility would require further design trade-off analyses.

None of the respondents has used active collision avoidance, although several have indicated an interest in pursuing this type of technique. Intelsat noted it is generally not practical to include an active beacon beyond the useful life of the satellite.[31] It would require a long-life power source and an omnidirectional antenna. Additionally, a beacon could cause radio interference to other satellite systems in service.

It would be especially important for Space Station Freedom to have the capability to perform avoidance maneuvers for debris, 10 cm or larger, that could be tracked by ground stations.[32] The NASA Johnson Space Center has been developing an onboard sensor for debris detection for improved resolution and tighter control-loop capabilities. Unfortunately, this project may become the victim of cost-reduction measures because there are no official programmatic requirements for it.

3) Techniques for minimizing debris released during the operation of spacecraft

At least four organizations have already developed means to retain operational hardware within the spacecraft environment. Some have and will continue to attach all potentially releasable items with lanyards.

Intelsat has tried to ensure that its satellites do not release any hardware.[33] Items are generally tied with lanyards or otherwise retained. Most of these techniques result from satellite manufacturer practices, since items related to debris generation have not been included in satellite specifications. This is the case with the Intelsat satellites purchased from Hughes, Ford Aerospace (Loral Space Systems), and TRW.

Use of alternate waste disposal techniques from piloted operations received relatively few positive responses, but this must be viewed in light of the fact that there are not many manufacturers or operators directly involved in human spaceflight activities. Boeing Aerospace is responsible for the development of the flight portion of the logistics system for the Space Station Freedom and has indicated that the trash and human waste will be dried, compacted, and stored for return to the ground by the Space Shuttle.[34] The only other nation that has had an active human exploration program in space, the [former] Soviet Union, has de-orbited the trash and human waste from its Space Station Mir for incineration in the atmosphere.

4) Techniques for minimizing the creation of fragments caused by explosions and collisions

The present use of techniques to avoid explosions generally has been limited to the previously discussed venting and depletion burns of rocket stages and some of the end-of-life GEO spacecraft safing. The survey identified additional potential measures, some in current general use and some planned for protecting spacecraft elements from explosion.

In particular, Space Station Freedom habitation elements, pressurized containers, and other critical elements will be shielded from impact by micrometeoroids and small orbital debris particles.[35] Intelsat will avoid explosions by building in sufficient burst margin for batteries and propulsion systems.[36] Such modifications, however, may result in substantial negative performance impacts, requiring cost/benefit trade assessments.[37]

Designs for the graceful degradation of components and systems have been considered for several future applications. Techniques received in the survey include the firing of all remaining ordnance, and emptying all propellants and pressurants at the end of useful satellite life.

The mitigation of effects due to unavoidable explosions or collisions generally has not been performed in the past, but future implementation appears promising, at least with regard to piloted vehicles, according to a number of responses. The Space Station Freedom program plans to reduce the risk from collisions and resulting debris by adding shielding.[38] The current SSF design requirements include the minimization of secondary ejecta and the use of materials that maximize resistance to hypervelocity impacts. The SSF plans also provide for augmentation of shielding as the facility grows and the debris hazard increases. ESA has similar plans for shielding of piloted vehicles.[39]

Summary of Survey Results

The following is a summary of the commonly practiced techniques and those favored by respondents for future implementation.

Design and operational techniques already used with varying degrees of acceptance:

1) Discarded rocket bodies:
   * Expulsion of excess propellants
   * Expulsion of excess pressurants
   * Minimization of independent launch vehicle parts allowed to reach orbit
   * Securing parts to the upper stages
   * Use of the COLA program.

2) Spacecraft that have terminated their missions:
   * De-orbit and controlled reentry--LEO spacecraft
   * Orbit maneuvering to shift spacecraft or components into disposal (graveyard) orbits (not a long-term solution).

3) Operational debris released from spacecraft during their missions:
   * Lanyards attached to all potentially releasable items such as camera lens and instrument covers, equipment used by astronauts in extravehicular activities, and other material
   * Structural attachment of otherwise detachable elements.

4) Fragments originating from explosions or collisions:
   * Increased shielding

In addition to the above, other measures appear to have widely acknowledged potential. Among these are:

1) Discarded rocket bodies:
   * Use of separation devices
   * Use of the COMBO program
   * Enhancement of the accuracy of the COLA program
   * Selection of launch times and dates to exploit natural forces for more rapid reentry of debris into the atmosphere.

2) Spacecraft that have terminated their missions:
   * Retrieval and/or reuse of spacecraft
   * Use of active beacons for spacecraft detection and avoidance.

3) Operational debris released from spacecraft during their missions:
   * Storing of trash and human waste, and return with logistics flights
   * De-orbiting trash and human waste for incineration in the atmosphere.

4) Fragments originating from explosions or collisions
   * Protecting and preventing hardware elements from exploding
   * Designing for graceful degradation of components and systems
   * Incorporating adequate shielding
   * Use of low fragmentation materials.

PRELIMINARY ASSESSMENT OF DESIGN AND OPERATIONAL PRACTICES

No formally adopted technical design or operations standards, guides, or even recommended practices currently exist for the mitigation of orbital debris. Nevertheless, the survey conducted through this study and supplemented by a review of the literature shows that there are already a number of voluntarily adopted and widely practiced techniques. Although certain techniques are more commonly practiced than others, there is an increased awareness of the need to use them and a trend toward their continuation, within both the public and private sectors.

The very existence of these voluntarily adopted design and operational techniques that reduce the amount of artificial debris in Earth orbit leads to several conclusions. One is that both the government and private sectors recognize that debris poses a potential hazard to operations in Earth's orbital environment. This is not a new finding in the context of government policies. Several recent government reports have focused on the problem and have strongly supported implementation of debris mitigation techniques. [40] The finding is significant, however, in terms of private sector actions, because any design or operational practices in that sector have been developed voluntarily, rather than in response to any government regulations or agreements, indicating some level of corporate self interest.

Debris mitigation practices that have been adopted separately by two or more manufacturers or operators and that have been shown to be effective indicate the most promising areas to be pursued in the near future. This is especially the case for mitigation techniques practiced by the space agencies or companies of more than one nation. That a certain mitigation technique has been successfully used in the operational and commercial space environment provides a presumption in favor of its technical feasibility and cost effectiveness. This, in turn, makes such a technique a logical candidate for closer investigation as a potential industry or regulatory standard.

Nevertheless, no particular debris mitigation technique currently practiced by any portion of the industry provides a sufficiently compelling rationale for that technique to become an industry-wide standard without further investigation and analysis. A number of technical and economic tradeoffs still need to be considered, and some of these are discussed in the next chapter.

The Study Group has identified four categories of debris mitigation measures that are the most promising candidates for near-term standardization, based on a preliminary technical assessment of the survey results and the current knowledge of the debris environment. These categories of techniques have been selected because of their demonstrated acceptance among a number of spacecraft manufacturers and operators, and because of their potential effectiveness in reducing the debris hazard.

1) Venting of residual fuel and pressurants from discarded rocket bodies. Debris from exploded rocket bodies (34 breakup events recorded as of 1991) accounts for over 1900 of the cataloged objects in Earth orbit. The venting of residual fuel and pressurants is a relatively simple and inexpensive technique already used in many U.S., European Space Agency, Japanese, and Russian launches, but it has not been adopted by all launching government agencies or companies. Although their exact cause has not been determined conclusively, the explosions of a Chinese upper stage in October 1990 and of a Soviet rocket body in March 1991 are two recent breakups that might have been prevented by a depletion burn.

2) Boosting of GEO satellites into disposal orbits. The satellite population in geosynchronous orbit is growing rapidly. The GEO is unique for communications purposes and for synoptic remote sensing observations, making it an important strategic and economic location. More GEO satellites have been deployed over the past decade than in all previous years combined, and the launch rate is expected to increase. There is no natural cleansing mechanism, such as atmospheric drag, so that any hardware deposited in GEO may remain indefinitely. A large number of GEO satellite operators in the U.S. and in other countries already use a variety of boosting techniques, some more effectively than others, near the end of useful life of their spacecraft. These techniques need to be evaluated fully from technical and economic standpoints, so that a common approach with a minimum set of performance standards will be instituted.

3) De-orbiting spent hardware. The majority of all orbital debris mass consists of rocket bodies and payloads abandoned after their use.[41] If left in space, this class of debris could provide a significant portion of the source material for a self-perpetuating sequence of collisions.[42] De-orbiting objects like these could significantly reduce the risk of collisions and the creation of hazardous fragmentation.

4) Reducing operational debris. Operational debris accounts for approximately 12 percent of all cataloged objects in Earth orbit. Operators of expendable launch vehicles, satellites, and piloted vehicles already have taken some corrective actions to reduce this type of debris. Their practices should be examined to determine the design penalties and cost tradeoffs in relation to their effectiveness in reducing harmful debris. The most beneficial designs should be recommended for universal use.

Techniques within these four categories of debris mitigation are important as preventive measures and as means of reducing the overall risk to missions in Earth orbit. Furthermore, a number of active removal and shielding practices have already been used and some are being planned for future deployment. However, shielding and especially active removal may be more expensive than preventive measures. The broad adoption of the most effective preventive measures by all launching states would defer and might obviate the need for more costly countermeasures.

ENDNOTES

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17. *Op. cit.*, n.12.
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4. ECONOMIC ASPECTS

Improved understanding of the economic issues associated with orbital debris is essential to forming effective debris mitigation policies and regulatory frameworks. In addition, consideration of the economic impact of debris--on the public and private sectors in the U.S. and elsewhere--is important in assessing the political acceptability of any proposed solutions to the problem. The Study Group has reviewed some analyses of economic issues, and some specific information about debris mitigation costs.[1] The discussion below identifies a number of relevant questions and issues that need to be addressed, and provides some preliminary conclusions and recommendations.

ECONOMIC IMPACT OF DEBRIS AND ITS MITIGATION

At the present time, much of the risk posed by orbital debris constitutes a *low-probability, high-consequence* event--that is, major debris impacts may not occur in all likelihood, but would have enormous consequences if they did. Estimating the consequences for space program quality, safety, and economics thus involves practical difficulties--namely, a lack of statistical data on the probabilities and their consequences. These difficulties in turn make it challenging to ascertain the adequacy of safeguards and, in the commercial sector, the extent of insurance coverage. It is also difficult to address the more philosophical matter of how safe is safe enough. In this regard, it is important to note that even relatively minor mishaps can be seen as indicative of larger, more systemic problems in space activities.[2]

Such estimates are a task for future research. Nevertheless, an overview of some possible probabilities and consequences is provided below.

Space debris consists of both naturally occurring micrometeoroids and artificial sources. Artificial debris has grown rapidly in relation to the constant micrometeoroidal flux since the dawn of the space age, and now surpasses it in total mass and in flux rates for most size impactors in near-Earth space at any given time. This trend is likely to continue as more nations and commercial entities acquire the capability to operate in Earth orbit. Despite the reasonably well-documented increase in the amount of orbital debris, no serious damage to operating spacecraft is known with certainty to have occurred to date. Still, as discussed in Chapter 2, significant uncertainties remain regarding the current nature and extent of the problem, as well as its future growth.

The unabated growth of orbital debris could result in an unstable environment in a matter of decades, created by a cascading ("runaway") series of collision-induced breakups. Certain frequently used orbital bands would be rendered unacceptably hazardous for piloted and most robotic spacecraft operation.[3] In such an eventuality, some bands would become locations of particular concern before others because of their favored use. This could have a serious impact not only on the multibillion dollar aerospace industry, but on the many important applications from space--telecommunications, navigation, weather forecasting, environmental monitoring, national security, and more--on which we rely increasingly.

The 1989 interagency Report on Orbital Debris, extrapolating the growth of debris in orbit from past and existing trends, indicated that the probability of a 1-cm or larger object striking a space station-class spacecraft (~5000 m^2, similar in size to the space station being proposed by NASA in 1988) in the 2010 time frame may be as high as one collision every two years.[4] A 1-cm aluminum sphere impacting with a relative velocity of

10 kilometers per second produces the kinetic energy equivalent of a 200-kilogram safe moving at 100 kilometers per hour.[5]

Since the writing of the 1989 report, however, both the size of NASA's Space Station Freedom (SSF) and the projected launch rate have decreased substantially. This has resulted in a concomitant decrease in NASA's estimated probability of a catastrophic collision to 1:10 for the period 2000-2010.[6]

For a typical small spacecraft with a surface area of ~40 square meters at 500 kilometers above the Earth, the chance of a catastrophic collision with a 1-centimeter or larger particle has been predicted by NASA to be as high as 1:110 per year by the year 2010--a risk sufficiently great to require consideration of shielding[7] and the use of avoidance maneuvers. In the case of the SSF, the shielding requirements are being augmented to reflect higher risk factors than those assumed in the mid-1980s, when those requirements were first established.[8] The cost of shielding depends on many factors, including the specified lifetime of a spacecraft, exposed area, operational altitude, location of critical components on a spacecraft, redundancy levels, and fault tolerance capabilities.

A catastrophic collision with a piloted spacecraft--regardless of its country of origin--likely would have a deleterious impact on all space programs, both in terms of funding and implementation. Yet even a significantly increased risk to normal spacecraft operations, short of catastrophic results, could increase the cost of many currently routine activities in space as a result of higher design and operational costs, and insurance premiums. Although uncertainties about both the existing and projected orbital debris population remain, it appears that even a small increase in orbiting materials over what is generated at current launch levels, without any corresponding mitigation, could prove to be costly and disruptive to large space programs.

COST-BENEFIT TRADEOFFS

It is essential to determine what are the performance penalties and related cost tradeoffs associated with each debris mitigation technique. What are the most cost-effective designs and operational procedures in each debris mitigation category?

In evaluating the tradeoff of costs versus mitigation effect, a number of potentially negative factors should be considered including: performance loss, reduced structure, reduced system redundancy, useful lifetime reduction, early termination of satellite life either by de-orbiting or by boosting to a graveyard orbit, increased operational complexity, and a possible increase in the risk of failure propagation. In determining the overall effectiveness vs. cost, it is also important to consider the frequency of mission vs. net effect on debris growth. The worst case is a high frequency mission that is also a large debris source, whereas the best case is a low frequency mission that is a small debris source.

The direct costs associated with existing design and operational mitigation practices range from the negligible to the very expensive. In general, however, it would be less expensive to limit the growth of debris in Earth orbit rather than attempt to reduce it to acceptable levels once it is there. Moreover, most of the minimization techniques recommended as most promising for broad acceptance in the near future are currently being used by a portion of the world's aerospace industry and launching states. Those used by private sector manufacturers and operators, in particular, may be presumed to indicate that the costs are not prohibitive.

DISTRIBUTION OF WINNERS AND LOSERS

It may not be readily apparent who stands to lose and gain from either the increase of debris in Earth orbit or from its minimization. In particular, how should a *net* benefit measure take into account both actual and perceived factors such as equity, prestige, national security, and public safety across industrial competitors within a country (for example, dirty vs. cleaner launch vehicles) and across countries (for instance, incumbent users of space vs. new or emerging users;

rich vs. poor)? Is the harm from debris unidirectional (imposed by one party on another), reciprocal, regional, or global?

The general aerospace industry, all direct users of space programs, and the taxpayer are all potential losers if the growth of debris is not abated. Although large-scale disruption or denied use of space assets and their applications would be a serious matter, the harm is unlikely to be evenly distributed. Those operators of spacecraft in the most heavily polluted regions would bear a disproportionate burden. Moreover, those who can afford comprehensive insurance, and have an extensive technological infrastructure and contingency plans generally will fare better than those with more limited means.

It is also important to note that if the orbital environment becomes significantly more dangerous for long-term operations, it may well become cost effective--or even profitable--for industry to develop and implement programs for the active removal of artificial debris from certain areas, or the conversion of debris to some useful purpose. A number of concepts for debris removal or reuse have been proposed in recent years and several feasibility studies are in progress.[9] Although most of these technologies are not yet mature or cost effective, the best of them may emerge as successful commercial ventures in the longer-term, much like the environmental hazard control or clean-up industries here on Earth. Furthermore, those industries that compete with space-based applications, such as fiber-optic communication systems versus communication satellites, may gain considerable new business. Nevertheless, some space-based applications, such as global environmental monitoring or microgravity research, do not have direct, or cost-effective, ground-based counterparts.

The biggest users of the Earth's orbital environment enjoy near-term economic advantages from unrestricted operations, but also face large economic and other losses in the event that the debris reaches uncontrollable levels. The question of how to respond to an uncertain, but serious threat, goes to the heart of the dilemma facing all launching states, for it remains unclear whether an aggressive program to reduce the amount of debris deposited in orbit would be cost-effective at this time.

SCOPE AND TIMING

It is important to ascertain, as well as possible, how sensitive net benefits are to the degree and pace of debris accumulation and mitigation. This is, should we mitigate a lot or a little, sooner rather than later, in some categories of debris rather than others?

Debris in the Earth orbital environment is a multidimensional problem. Different orbits have different environmental attributes that impact the manner in which orbital debris propagates, as well as the way in which spacecraft operations are conducted. Any debris mitigation measures therefore are also dependent on orbital altitude, the type of spacecraft being operated, and the category of debris that is being prevented. Many of these specific factors were no doubt considered by the manufacturers and operators who have already implemented the various mitigation practices discussed in the previous chapter. That these practices are being voluntarily used in an operational environment suggests that they may be the most suitable approaches to consider for widespread implementation in the near future.

A broad range of responses is possible, from the laissez-faire to the draconian. On the one hand, there are those who urge a cautious approach, preferring to study the problem further, to reduce the uncertainties that currently undermine accurate predictive capabilities, and to refrain from any actions that would have any negative economic consequences. Although an improved knowledge base might be expected to result in more efficeint responses, the inherent risk in this approach is that if the problem turns out to be worse than anticipated, little will have been done to reduce its severity or to prepare ourselves to respond in a timely way.

On the other hand, those who believe that quick action is necessary to prevent or even to reduce the accumulation of debris in orbit, discount the importance of the scientific uncertainties; they focus instead on the growing sources of debris, which are well known. They consider immediate stabilization of the debris population and a no net gain policy to be the only responsible courses of action, given the difficulty in responding in a timely and effective manner once the problem has become obviously manifested. The inherent risk in this approach is that we may create greater economic dislocation now, with unnecessarily severe cost impacts, than if the scope and nature of the problem were better understood.

This situation, with a potentially serious problem identified, but with little immediate impact and an uncertain future, argues against an either-or policy. Instead, an appropriate balance needs to be achieved, one that supports low-cost and effective mitigation practices as insurance against a catastrophic situation, but that does not unduly compromise either short- or long-range programmatic flexibility and economic growth. Other, less tangible, factors such as equity, political prestige, national security, public safety, and environmental quality, also need to be considered to achieve an optimum balance.

IMPACTS ON TECHNOLOGICAL INNOVATION

The advance of technology is an important consideration in developing a comprehensive approach to reducing debris in orbit. In those cases in which individual companies and agencies have instituted specific design and operational practices regarding debris mitigation, it may be presumed that the impact--whether positive or negative--on technological innovation has been an element in the decision-making process. A design or practice that benefits one company or agency, however, will not necessarily benefit all others in the same way. To date, none of the debris mitigation measures has been universally adopted. This indicates that the question of their universal benefit, including any impact on technological innovation, remains open. At the same time, the absence of universal adoption of certain debris mitigation practices may be the result of inadequate availability of information or poor management, rather than a negative appraisal by those parties that have not adopted those practices. Finally, a technological advance may be far more productive or efficient than the technology it replaces, yet much more environmentally destructive. Thus, in any analysis of space technologies, it is important that the usually hidden environmental costs be factored into the assessment.

PRELIMINARY CONCLUSIONS

Accurate and comprehensive information about the technical and environmental dimensions of orbital debris is crucial to developing complete answers to the issues raised above. It is especially important to reduce uncertainties in the characteristics, magnitude, and rate of growth of debris. Such technical data are essential to further economic analysis. For example, information about launch vehicle weight penalties or other performance impacts due to mitigation requirements can indicate the relative costs of various mitigation strategies. This type of information would help establish appropriate priorities in the development of policies. Information about the nature and availability of technologies to monitor compliance with any nationally or internationally adopted debris minimization strategies is essential as well. Despite the notable lack of publications regarding the economic aspects of orbital debris and related mitigation efforts, some preliminary conclusions can be drawn from recent government reports and from the results of our survey.

The growth of orbital debris, if left unchecked, will increasingly endanger many, if not most, of the activities we carry out in Earth orbit. The cost of all future activities is likely to increase over the long term, and may eventually make certain functions prohibitively expensive, or even physically impossible. ***It is essential for the United States to protect its long-term strategic, economic, and scientific interests in space and to preserve the ability to operate effectively in Earth***

orbit.

Measures taken to prevent or reduce the orbital debris hazard before it becomes significantly worse are likely to be less expensive than developing and implementing active countermeasures for dealing with a more hazardous debris environment. This is particularly true for existing debris mitigation measures that are known to have relatively low costs and that are readily available.

An appropriate balance, therefore, needs to be achieved in addressing the orbital debris problem, one that supports low-cost and effective mitigation techniques as insurance against a catastrophic situation, but does not unduly compromise either short- or long-range programmatic flexibility and economic growth. In order to avoid placing the U.S. space industry at a competitive disadvantage, mitigation techniques that are proposed for technical or regulatory standardization in the U.S. must also be pursued and adopted internationally, in most cases.

Table 4-1 Preliminary Technical and Economic Assessment of Debris Mitigation Techniques

Mitigation Techniques (in priority order)	Debris Prevented	Technical* Implementation	Cost*	Status
Venting residual fuel/pressurants from discarded rocket bodies	Large number, moderate mass	Simple	Low	Broad use in U.S., Europe, Japan, Russia; more planned
Boosting GEO satellites into disposal orbits	Small number, large mass (debris shifted not removed)	Moderate	Moderate to high, depending on disposal orbit	Some use internationally; more planned
De-orbiting spent hardware at end of operational life	Small number, large mass	Moderate to difficult	Moderate to high	Very limited use; more planned
Reducing operational debris	Moderate number, small mass	Simple to moderate	Low to moderate	Some use; more planned

* Values assigned to technical implementation and cost are relative to each other, and may vary significantly by payload type.

In addition, the Study Group finds that the absence of a thorough analysis of the costs and economic considerations associated with the orbital debris problem severely undermines the capability to assess all options. A comprehensive economic analysis of orbital debris and its mitigation, sponsored by the relevant government agencies but performed by one or more independent organizations or contractors, is strongly recommended.

As discussed in the previous chapter, the results of our technical survey demonstrate that effective design and operational debris mitigation practices are already used on a voluntary basis by a number of government and private sector parties. The voluntary adoption of debris mitigation practices in the operational environment suggests an acceptable cost-benefit ratio, and makes those practices currently in use appropriate near-term candidates for technical standardization and adoption on a wider scale. Table 3-1 summarizes the Study Group's preliminary technical and economic assessment of the most promising orbital debris mitigation techniques.

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4. *Ibid.*, pp. 14-15.
5. *Space Debris a Potential Threat to Space Station and Shuttle*, U.S. General Accounting Office, April 1990, p. 2.
6. Memorandum from Andrew Edwards, NASA Code MT, to Richard Weinstein, NASA Code QT, January 9, 1992.
7. *Op. cit.*, n.2, pp. 15-16.
8. *See*, "Restructuring, Debris Drive Need to Augment Station Shielding," *Aerospace Daily*, Vol. 160, No. 157, pp. 470-71, December 24, 1991.
9. For instance, the External Tanks Corporation (ETCO) has developed several potential uses in Earth orbit for the Space Shuttle external tanks that are discarded during each Shuttle launch. One of these proposed uses consists of forming a debris shield for the Space Station Freedom with those tanks. Private communication to the study chairman from Philip Culbertson, ETCO, May 16, 1991.

5. LEGAL ASPECTS

INTRODUCTION

The voluntary adoption of some design and operational techniques for reducing the growth of various categories of orbital debris may be seen as an encouraging development. It demonstrates that there are some technologically mature and economically feasible measures that can be readily applied in minimizing debris.

Although current industry initiatives are laudable, they are not sufficient. A well-organized and focused effort to implement effective debris mitigation techniques on a pervasive basis is necessary.

There are two distinct, yet interrelated methods to implementing solutions to the orbital debris problem—a **technical** and a **legal** approach. The technical approach is driven by perceptions of self interest and relies on the engineering community, both within and outside government, to cooperate on a worldwide basis in developing a technically and economically sound set of solutions to well-defined problems. To be effective, such a collaborative effort must be supported through participation of technical experts from government agencies, the aerospace industry, and related professional societies on an international basis. The technical approach aims at establishing technical standards or recommended practices for spacecraft design, operation, or performance. Typically, such standards or recommended practices would be set forth in a technical memorandum of understanding between government space agencies, or in a document developed by an industry association.

The legal approach, while deriving expert advice and guidance from the engineering community, uses legislation, administrative orders and regulations, and intergovernmental agreements or treaties to impose solutions from above. For example, national regulatory agencies, such as the Department of Transportation's Office of Commercial Space Transportation, could adopt regulations imposing spacecraft performance requirements aimed at reducing debris generation in connection with launch vehicle operations. Similarly, international organizations or conferences could adopt such requirements by way of a treaty, which would be binding on ratifying or adhering members or States.

This is not to say that the technical and legal approaches are incompatible; rather, they complement each other. Indeed, it is not uncommon for a technical standard to be codified, and the existence of a standard itself may have significant legal ramifications.

In any event, ***no technical standardization and only minimal legal regulation pertaining to the mitigation of orbital debris currently exists either in the U.S. or internationally***. A brief overview of the relevant U.S. and international legal provisions and regulatory institutions is presented in this chapter, followed by a discussion of some options that could be pursued in rationally implementing effective debris mitigation techniques.

DOMESTIC LEGAL AND REGULATORY CONSIDERATIONS

Only in the past few years has the U.S. government begun to form a policy on orbital debris and to coordinate federal agency activities, as noted in Chapter 1. Although the November 1989 Presidential Directive on a National Space Policy mandated that "all space sectors will seek to minimize the creation of space debris," no legislation or administrative rulemaking has formally implemented the broad thrust of that policy in the civil sector.

Three separate statutory regimes regulate the operation of private commercial space activities: the 1984 Commercial Space Launch Act[1] governs space transportation; the 1934 Communications Act[2] and the 1962 Communications Satellite Act[3] control satellite communications activities; and the 1984 Land Remote-Sensing Commercialization Act governs satellite remote-sensing.[4] Although none of these legislative acts refers specifically to orbital debris, their scopes appear to be sufficiently broad to provide the implementing agencies with the necessary authority to impose regulations for orbital debris management. Any such provisions, of course, must be implemented pursuant to proper rulemaking procedures.

The National Aeronautics and Space Act of 1958 establishes the basic national space policy and regulates the activities of the National Aeronautics and Space Administration (NASA), but it makes no reference to orbital debris.[5] Following the February 1989 interagency *Report on Orbital Debris*, however, NASA and the Department of Defense (DoD) were charged with leading a continued interagency effort to address the orbital debris problem. Representatives of the three agencies that license commercial space activities were to continue discussions "to define the boundaries of regulatory authority among the licensing agencies over commercial activities that may produce orbital debris." [p.52] Since that report was published, however, only the DoD has issued related regulations.[6] What follows is a brief overview of the federal agencies' existing authority to regulate orbital debris.

Authority of Governmental Agencies to Regulate Space Debris

The Office of Commercial Space Transportation (OCST), the Federal Communications Commission (FCC), and the National Oceanic and Atmospheric Administration (NOAA) respectively regulate private launch vehicles, telecommunications satellites, and space-based remote sensing activities. None of these agencies currently imposes debris mitigation requirements, although the OCST does consider debris generation as part of a general safety and environmental assessment conducted during the licensing process. Each agency has the authority to impose design and operating requirements on spacecraft operators for the purpose of minimizing the creation of debris in space, subject to the appropriate rulemaking proceedings.

NASA is responsible for regulating and controlling debris created by its own space activities. The agency has not yet formulated an official, comprehensive policy or strategy to deal with the debris problem, although it is working on that task on a number of levels, including a revised safety policy.

Office of Commercial Space Transportation

Section 7 of the 1984 Commercial Space Launch Act (hereinafter CSLA), empowers the Secretary of Transportation to issue a license for launching of a space launch vehicle "consistent with the public health and safety, safety of property, and national security interests and foreign policy interests of the United States."[7] Pursuant to CSLA Section 6(b)(2), the Secretary of Transportation also has certain jurisdiction over foreign payloads launched by U.S. corporations, and over U.S. commercial payloads that are not subject to regulation by the FCC or NOAA, to ensure these payloads will not "jeopardize the public health and safety, safety of property, or any national security interest or foreign policy interest of the United States." The mandate is sufficiently broad to encompass the regulation of the debris aspect of the launch and the payloads. CSLA Section 8(b), provides that the Secretary of Transportation may impose additional requirements with respect to launches as are necessary to fulfill the statutory mandate. The authority given to the Secretary of Transportation under these provisions has been delegated to the OCST, which has issued regulations.[8]

Federal Communications Commission

Section 1 of the 1934 Communications Act created the Federal Communications Commission for the purpose of "regulating...communications...by radio so as to make available, so far as possible, to all people of the United States a rapid, efficient, nationwide and worldwide...radio communication service...." [9] The statutory authority may be broad enough to allow for debris-related regulation of telecommunications satellites since, in the absence of such regulations, debris would pose a risk of collision that could impede the communication services that the FCC is charged with promoting. Also, "[t]he Commission may perform any and all acts, make such rules and regulations, and issue such orders, not inconsistent with the [Communications] Act, as may be necessary in the execution of its functions."[10]

National Oceanic and Atmospheric Administration

The 1984 Land Remote-Sensing Commercialization Act (hereinafter LRSCA), authorizes the Secretary of Commerce, subject to the approval of the President of the United States, to impose requirements with respect to the disposal of a remote-sensing satellite upon termination of a licensee's operations.[11] The statutory authority appears broad enough to include a requirement for a satellite's controlled reentry into the atmosphere. The Act authorizes the Secretary of Commerce to impose conditions on the granting of a license,[12] and this authority of the Secretary of Commerce has been delegated to NOAA.

Department of Defense

The scope of this report does not include consideration of military space activities, the creation of orbital debris as a result of those activities, or their regulation. However, the regulations issued by the U.S. Space Command in June, 1991, on "Minimization and Mitigation of Space Debris" have provisions that might serve as models for the civil sector agencies (see Figure 5.1).

Department of Defense
Headquarters United States Space Command
Peterson AFB, CO

USSPACECOM REGULATION 57-2

6 June 1991

MINIMIZATION AND MITIGATION OF SPACE DEBRIS

This regulation implements the USSPACECOM policy and guidance from national and defense authorities for mitigating the proliferation and effects of space debris upon military space systems.

1. BACKGROUND: The DoD Space Policy of February 1987 states that the DoD will seek to minimize the impact of space debris on its military operations. The National Space Policy of November 1989 reiterates and expands the 1987 DoD Policy on space debris, applying it not only to the national security sector, but to civil space activities as well. Design and operations of DoD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements.

2. RESPONSIBILITIES: The following shall guide the operation, development, and conception of current and future space systems.

a. Through its component commands, USSPACECOM will foster activities to better understand the evolution of space debris and the hazards of orbital debris to military, civilian and commercial space activities.

b. Component space commands shall increase awareness of the requirement to mitigate space debris. They shall monitor space debris mitigation efforts of their material development activities, and, within their authority, assure that mitigation of space debris is addressed explicitly in all space systems developments and upgrades.

c. The design and documentation process for space system development, modification, or upgrade will permit clear identification of cost, schedule, and performance impacts of efforts to mitigate debris. System development or modification tradeoffs which affect the above in order to minimize debris shall be reviewed by and approved by the affected Service component space commands and coordinated with the United States Space Command.

d. The justification for measures to mitigate and minimize debris or the effects of hypervelocity impact upon space systems should reflect robust technical investigation and research. Component Commands shall focus research to quantify cost, schedule, and performance impacts on system development.

Donald J. Kutyna
General, USAF
Commander in Chief

Figure 5-1 Reprint of U.S. Space Command Regulation 57-2

Options for Incorporating Orbital Debris Mitigation Requirements into the U.S. Regulatory Framework

The principal finding of the 1989 Interagency Group *Report on Orbital Debris* was that additional information on the debris environment, its trends, and its implications was necessary for any consideration of policies, regulations, standards, or other actions. It was noted that without better knowledge of the environment, there was uncertainty about the urgency for action and the effectiveness of any particular mitigation measure.

Since the writing of that report, therefore, the focus has been on additional research. The government position was that once the appropriate agencies, mainly NASA and DoD, have better defined the debris environment, characterized the threats posed by the environment, and identified options for dealing with the threats, the Interagency Group would again begin to consider possible actions. At that point, the agencies with regulatory responsibilities and links to private industry would begin to look at cost-effectiveness issues and obtain input from commercial operators.

From these inputs, appropriate measures could be considered. In some cases, these could take the form of recommendations for national policies or standards. In other instances, they would be inputs into already existing regulatory processes. They could also take the form of voluntary principles.

Moreover, once there is a better understanding of U. S. positions on these various issues, any existing international relationships could be expanded from being purely research-oriented in nature to including consideration of international regimes which parallel U. S. actions, whether regulations, treaties, principles, or other mechanisms. These could be bilateral, multilateral, or within international organizations.

As a result of the progress made by some of the agencies in improving the understanding of the orbital debris problem since the 1989 report, the interagency consultative process was restarted in December 1991. Since then, the Interagency Working Group on Orbital Debris (IWG-OD, as it is now called) has been reviewing the progress of the agencies over the past three years and planning the next series of actions.

The Study Group agrees with the government approach, in principle. In placing a greater emphasis on the long-term threat of the orbital debris problem, however, the Study Group finds that more could be done now to support low-cost and effective debris mitigation techniques as insurance against a potentially catastrophic situation.

Despite some interagency coordination and the activities already funded and in progress, there are a number of areas that would benefit from increased attention. A conspicuous gap has been the lack of involvement of the FCC and NOAA in the interagency process, as well as the absence of any substantial effort to address orbital debris issues within those two agencies. As documented in Chapter 3, several spacecraft operators already are performing end-of-life boost maneuvers for removal of spacecraft from GEO. Many of these operators fall within the jurisdiction of the FCC, yet this agency has no program underway to develop even a minimum set of guidelines to help ensure that the operators use spacecraft disposal and other debris mitigation techniques consistent with the best interests of all GEO users. This issue will soon become important in LEO as well, because several companies are seeking to introduce multisatellite communications constellations at lower altitudes.

Similarly, there has been little effort on the part of NOAA to investigate debris mitigation techniques within the context of its regulatory responsibilities for commercial land remote sensing systems. Although there is significantly less activity in the commercial remote sensing sector than in the communications satellite area at this time, NOAA is itself an operator of meteorological spacecraft in both LEO and GEO. To date, NOAA has not taken any debris mitigation measures with regard to its deactivated LEO polar orbiting satellites, and the agency's spacecraft disposal methods for GEO have not been consistently implemented.

Since there are already some orbital debris mitigation techniques in practice, greater attention should be given to implementing the most technically mature and least costly of these on a broad basis in the next few years. To the extent that any of these measures will be implemented unilaterally by the U.S., or not fully adopted by all launching states, special care must be taken to ensure that the competitive position of the U.S. will not be unduly adversely affected.

The Study Group is encouraged that the previously limited coordination effort of NASA-DoD-DoT is now being expanded to include the relevant expertise and involvement of the other federal agencies that have a significant interest in space activities—notably NOAA, DoE, and FCC. The following activities should be strengthened or initiated under the leadership of the National Space Council, in addition to the program conducted up to now by NASA-DoD-DoT:

1) Significantly increase our capability to characterize accurately the orbital debris environment and to develop more realistic models to predict future trends.

2) Expand government-industry interaction already begun by NASA, with full involvement of the relevant engineering societies in developing common debris-reduction technologies, practices, and standards.

3) Allocate adequate resources for implementing the most cost-effective and operationally proven debris mitigation techniques on a voluntary, industry-wide basis in the near term.

4) Conduct intensive research on the most promising technologies that require further development, and thoroughly investigate all economic aspects related to the creation and minimization of orbital debris.

Given the continuing worsening of the orbital debris problem, and the inevitable delays that would be experienced in confronting it only through voluntary action, however, ***careful consideration also should be given to accelerating the implementation of debris minimization measures through the judicious use of various national policy instruments, including incentives and regulations.***[13] Incentives can be used to encourage spacecraft manufacturers and operators to incorporate debris minimization techniques into their production and management plans. An effective method for introducing such incentives could be through the military and civilian procurement process, given the large number of spacecraft, launch vehicles, and space services procured by the government. Incentive instruments also might include monetary or other penalties on "dirty" technologies, financial inducements such as tax credits for "clean" technologies, and perhaps even orbital debris analogies to transferable emission rights (tradeable debris reductions, tradeable credits) such as those recently instituted under the Clean Air Act of 1990.[14]

In general, regulatory provisions could mandate certain standards of conduct and include controls on consumption (required product attributes, quotas, and even bans), production (restrictions on products or substances), and factors in design or production (standards of efficiency or durability).[15] As pointed out in the interagency *Report on Orbital Debris*, the *Regulatory Program of the U.S. Government* sets forth three principal functions of Federal regulations: 1) the direct control of commerce and trade, i.e., traditional economic regulation; 2) the protection of public health and safety and the environment; and 3) the proper management and control of Federal funds and property.[16] The regulation of activities that produce orbital debris falls under the second category, although the first and third function may also be involved, depending on the sector that is being regulated.

The use of incentives is generally preferable to regulatory action, because incentives are less obtrusive and can be used to influence decision-making within a market- or choice-based framework, rather than imposing a prescribed mode of conduct.

Nevertheless, selective use of regulatory mechanisms can help guide the informal technical coordination process. Specifically, there are several actions that could be taken by the three agencies that have regulatory responsibility for the commercial sector.

The Office of Commercial Space Transportation regulations for launch vehicles, set forth in 14 CFR Chapter III, could be expanded in several respects. For example, evaluation criteria and standards for debris mitigation could be incorporated into the safety and mission reviews conducted by the OCST prior to granting any license. A *space environmental impact statement* could require launch vehicle operators to assess the orbital debris impact of their missions. Such a provision might be added, e.g., to 14 CFR 415.33, called "Environmental Information."

The Federal Communications Commission regulations for telecommunications satellites, found in 47 CFR Part 25 (for domestic and international fixed communications, radiodetermination, and mobile satellites) and in 47 CFR Part 100 (for direct broadcast satellites), could be similarly extended. A requirement that satellite operators assess the debris impact of their missions, as well as end-of-life boosting requirements, could be implemented, e.g., in 47 CFR Part 25.

The National Oceanic and Atmospheric Administration's Regulations for Licensing Private Land Remote-Sensing Space Systems, set forth in 15 CFR Part 960, likewise could be amended to address this problem. Requirements that satellite operators assess the orbital debris impact of their operation, as well as end-of-life de-orbiting requirements could be implemented as part of 15 CFR 960.11, Criteria for Approval or Denial (of a license).

The Study Group recommends that the Office of Commercial Space Transportation, the Federal Communications Commission, and the National Oceanic and Atmospheric Administration, in coordination with the other agencies, issue a Notice of Inquiry with regard to the suitability and desirability of imposing design and operational standards for minimizing the creation of orbital debris. Such a notice should provide suggested minimum standards for comment by all interested parties. Emphasis should be placed on debris mitigation techniques already in use by entities within each agency's regulatory scope. Adequate resources for carrying out these tasks should be specifically allocated.

These Notices of Inquiry would provide the space industry and other interested parties an opportunity to comment on the current orbital debris situation, and on existing industry mitigation practices and preferred future measures. The technical information gathered during this process would help the agencies consider appropriate rules or standards that might be adopted for minimizing the accumulation of orbital debris.

Prior to adopting such a rule or standard, a Notice of Proposed Rulemaking would have to be issued by the respective agency. This Notice would be subject to comment, and would give industry and other interested parties an opportunity to oppose, or support, the proposed rule. Because this process could take several years, it is important for these agencies to begin as soon as possible. Nevertheless, any regulatory action should be considered in the international context, as discussed below.

INTERNATIONAL LAW AND REGULATION

All activities in outer space are inherently international. Solutions to any problems created by those activities, including the mitigation and management of orbital debris, ultimately must be addressed on an international level. This section reviews the current status of international law and the principal forums for addressing orbital debris issues, and provides some options for the U.S. to consider in the international context.

Current Status of Orbital Debris in International Law

Existing international law does not adequately address the orbital debris problem.[17] A handful of provisions scattered throughout United Nations space treaties provide little more than general discouragement and vague admonitions to would-be space polluters.

The 1967 Outer Space Treaty[18] addresses environmental issues to a greater degree than any other space treaties to which the U.S. is a party. However, neither its Articles nor the official records of the negotiations within the U.N. provide the Treaty with sufficient legal authority to use it as a mechanism for preventing or abating orbital debris.

The 1972 Liability Convention,[19] the purpose of which, among other things, is to compensate those whose space objects are damaged in space, may not apply to all types of orbital debris. The Liability Convention imposes liability when damage is caused "by a space object," but this term, as defined in the Convention, may not encompass operational or fragmentation debris, which together account for the vast majority of debris pieces in the orbital environment. It is even unclear whether "space object" would encompass spent rocket bodies and inactive payloads. The official records of the Liability Convention's negotiation history show that the drafters contemplated operational spacecraft as damage-causing objects. Due to problems in identifying most orbital debris, recovery may elude the victim even if the Liability Convention were to apply.

In the absence of any applicable governing treaties or other international agreements, international law recognizes other sources of law as being relevant. These include, in descending order of priority: international custom, as evidence of a general practice accepted as law; the general principles of law recognized by civilized nations; and judicial decisions and the teachings of the most highly qualified publicists.[20] In the case of orbital debris, these collateral legal sources would include the legislation and regulation of individual nations, as well as the actual practice of spacecraft operators accepted as law. Because the United States is one of the most active spacefaring nations, its laws and practices take on added significance in an area of activity that is not controlled by international treaties or other governmental agreements, especially if the launch activity of the [former] Soviet Union continues to decline.

International Forums

Nongovernmental Organizations

Several international nongovernmental organizations or groups have the competence to address various aspects of the orbital debris problem. Among the most active of these organizations are the Committee on Space Research (COSPAR) of the International Council of Scientific Unions, the International Astronautical Federation (IAF), the International Institute of Space Law (IISL), the International Academy of Astronautics (IAA), and Technical Committee 20 of the International Organization for Standardization (ISO). With the exception of the ISO, all of these organizations have sponsored sessions on orbital debris at their conferences, which have been very useful for international exchange of views and information.

Working Group 6 of the ISO Technical Committee on Aircraft and Spacecraft (TC 20) recently took up the task of developing technical standards for orbital debris mitigation. Its first project will be to develop an internationally accepted set of definitions for important orbital debris terms and concepts, an essential first step toward any meaningful international discussion and agreement on the control of orbital debris.

Governmental Organizations

The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) already has drafted and the United Nations General Assembly (UNGA) has promulgated five proposed treaties and two important resolutions regulating space activities. Although the UNGA clearly has the authority to place orbital debris on the COPUOS agenda, it has not yet done so. There is increasing interest within the COPUOS to take up the orbital debris problem.

The 1990 annual COPUOS Report to the UNGA states:[21]

> The Committee noted that the General Assembly, in its resolution 44.46, had recommended that more attention should be paid to all aspects related to the protection and preservation of the outer space environment, especially those potentially affecting the Earth's environment.
>
> The Committee also noted that the General Assembly, in the same resolution, had considered that it was essential that Member States pay more attention to the problem of collisions with space debris and called for the continuation of national research on the question.
>
> The Committee agreed that space debris was an issue of concern to all nations and that it could be an appropriate subject for discussion by the Committee in the future.

The International Telecommunication Union (ITU) manages the use of the radio spectrum for international telecommunications (including satellite telecommunications). Headquartered in Geneva, Switzerland, the ITU now has over 160 Member States. The organization first concerned itself with space communications in 1959 and, since then, has taken an increasingly active role in the regulation of satellite communications. Although the ITU's primary focus with respect to satellites is their use of the frequency spectrum, the ITU does exercise ancillary jurisdiction over the geostationary orbit. In view of broadly worded purpose clauses in its charter, the 1982 International Telecommunication Convention[22] (ITU Convention), the ITU may have sufficient authority to consider debris aspects of satellite operations. Under Article 4 of the ITU Convention, the ITU is required to "maintain and extend international cooperation between all Members . . . for the improvement and rational use of telecommunications of all kinds ..." and to "promote the development of technical facilities and their most efficient operation with a view to improving the efficiency of telecommunication services ... ."

Recent actions taken by the ITU's Consultative Committee on International Radio (CCIR) indicates that at least that subsidiary body of the ITU believes the organization has some measure of jurisdiction over the debris aspect of geostationary satellites. On June 12, 1991, a CCIR Study Group formulated a draft recommendation, entitled "Environmental Protection of the Geostationary Orbit." It states:

"The CCIR,

CONSIDERING

(a) that satellites are designed as fragile structures that have little survivability in case of a collision in orbit;

(b) that telecommunications functions of a satellite would be lost or at least degraded by a collision in orbit;

(c) that satellite break-up due to a collision would create a cloud of orbital debris that would dissipate around the orbit, increasing the collision probability within that orbit;

(d) that a satellite drifting in the orbit after the end of its life may block RF (radio frequency) links of active satellites;

RECOMMENDS

(1) that as little debris as possible should be released into the geostationary orbit during

the placement of a satellite in the orbit;

(2) that every reasonable effort should be made to shorten the lifetime of debris in a transfer orbit (see Annex I, not included here);

(3) that a geostationary satellite at the end of its life should be transferred, before complete exhaustion of its propellant, to a supersynchronous graveyard orbit that does not intersect the geostationary orbit;

(4) that the transfer to the graveyard orbit should be carried out with particular caution in order to avoid RF interference with active satellites."

The AIAA Orbital Debris Study Group considers this to be an appropriate initial step to bring this issue on the ITU agenda. Nevertheless, any action taken by the ITU will necessarily be limited only to communications satellites.

Options for Incorporating Orbital Debris Mitigation Requirements into the International Regulatory Framework

There are many models in existence in international law showing how the process, form, and content of regulations are developed. In some cases, desired regulations are formed in annexes to constitutional conventions, in which annexes are more easily amended or updated than the convention itself. In other cases, the regulations are formally adopted as rules, which are then incorporated into the enabling convention by reference. In still other cases, there are recommended practices established and published, but these are generally hortatory and are not considered "binding."

The options for addressing the problems associated with orbital debris on the international level are also divided according to **technical** and **legal** regulation. The following list typifies the kinds of actions that may be taken.

Technical Cooperation

1) Voluntary unilateral practices and procedures;
2) Voluntary multilateral practices, procedures, and notifications;
3) Generally agreed, but nonbinding, recommended practices, guidelines, or standards;

Legal Regulation

4) Formal break-up and reentry notification and registration procedures;
5) Reciprocal rights between consenting states to inspect or consult; and
6) Required multilateral design standards and operating procedures.

This list is not intended to be exhaustive, but constitutes examples of regulatory actions in an ascending order of control. Those states that conduct spacecraft launches today generally will prefer to limit any near-term international activity to the first three examples listed, because these kinds of recommended actions will not constitute formal constraints on States' plans and programs. In any case, bringing the international community to an agreement in this area may be expected to be politically difficult.

Technical Coordination and Cooperation

The approach recommended by the Study Group for the U.S. to minimize the creation of orbital debris is suggested on an international basis as well. At a minimum, ***the same four initiatives recommended for implementation on the national level are likewise recommended for international action (see pg. 42).***

NASA has already begun a program of technical consultations with the space agencies of other countries.[23] Bilateral meetings have been held between NASA experts and space agency officials in Germany, France, Canada, the European Space Agency, the former Soviet Union, Japan, and China. ***The current government efforts need to be strengthened, however, and inte-***

grated into a well-structured process that:

1) involves all launching states;

2) provides a sustained focus to the principal problem areas;

3) allocates adequate resources to resolving the highest priority problems; and

4) systematically transfers proven debris mitigation techniques and technology among all parties subject to legitimate national security and economic competitiveness concerns.

This intergovernmental technical coordination effort should be paralleled by vigorous cooperation in the private sector, through a process of citizen ("track-two") diplomacy.[24] These steps are essential prerequisites for any subsequent--or parallel--negotiations to establish a formal agreement, as discussed below.

Development of Formal International Agreements

The development of a more formal structure for regulating orbital debris on an international basis can be comprehensively addressed either in the United Nations COPUOS, or in an ad hoc process independent of any established intergovernmental organization. Both options are discussed briefly below.

Historically, the COPUOS has dealt with three special kinds of space activities. In each case, the same process was followed. The complex of technical/legal/economic issues involved in direct broadcasting by satellite (DBS), remote sensing of Earth resources, and navigation satellite systems, were studied by special Working Groups of the COPUOS set up for those purposes. The Working Groups met repeatedly over a multi-year span to make technical and economic assessments and to recommend guidelines for the use of applications satellites. These parallel precedents, which were dealt with over several years, first in data collection studies and later in assessing needs for regulation, offer instructive examples of how the space debris issue might be addressed in the COPUOS.

Most nations are well aware of the problems of space debris and the issue has already been raised at the UNGA and at the COPUOS. Rather than opposing COPUOS consideration of these issues, the United States could propose to the UNGA the "Abatement of Orbital Debris" as an agenda item for the COPUOS and the creation of a special Working Group on Orbital Debris, first within the Scientific and Technical Subcommittee, and subsequently in the Legal Subcommittee.

Whether or not the orbital debris issue is taken up by the COPUOS, the United States should take the lead and invite all spacefaring nations, as well as public international spacecraft operating organizations, to participate in a conference to be held in a series of sessions. The first of these should be convened in the U.S. by the National Space Council in close consultation with U.S. space agencies and the Department of State. The initial meeting could take place after the federal agencies have completed all the activities on their short-term agenda for orbital debris.

The first session would provide the opportunity for an open exchange of information and consensus-building among interested parties, in a multilateral forum, regarding:

(1) common definition of technical and legal terms in the orbital debris context.

(2) orbital debris presently and potentially associated with national and multinational space programs; and

(3) spacecraft design and operating measures already practiced by some of the participants to reduce or mitigate the generation of debris, and that could be adopted by all nations involved in space activities.

At subsequent sessions, working groups could begin formulation of standards for spacecraft design and operation, with the goal of minimizing the creation of orbital debris. The subsequent meetings also could determine the level of commitment the participating parties would be willing to make with respect to compliance with any formally adopted standards. This more formal process should integrate and build upon the technical coordination and cooperation activities recommended above.

ENDNOTES

1. Commercial Space Launch Act, as amended, 49 U.S.C. sec. 2601, *et seq.*
2. Communications Act, as amended, 47 U.S.C. sec. 151, *et seq.*
3. Communications Satellite Act, as amended, 47 U.S.C. sec. 701, *et seq.*
4. Land Remote Sensing Commercialization Act, as amended, 15 U.S.C. 4201, *et seq.*
5. National Aeronautics and Space Act, as amended, 42 U.S.C. 250, *et seq.*
6. USSPACECOM Regulation 57-2, June 6, 1991.
7. *Op. cit.* n. 1, sec. 2606, *et seq.*
8. 14 CFR, Chapter III, Parts 400, *et seq.*
9. *Op. cit.* n. 3.
10. 47 U.S.C. sec. 154(i).
11. *Op. cit.* n. 4, sec. 402(b)(3).
12. *Ibid.*, sec. 403(a).
13. *See, Policy Implications of Greenhouse Warming—Synthesis Panel*, Committee on Science, Engineering, and Public Policy, National Academy Press, Washington, DC, 1991, pp. 62-63.
14. *See*, Passell, Peter, "A New Commodity to be Traded: Government Permits for Pollution," *The New York Times*, July 17, 1991, p. 1, 14.
15. *Op. cit.*, p. 13.
16. *Regulatory Program of the U.S. Government*, Executive Office of the President, Office of Management and Budget, April 1, 1985-March 31, 1986, at page xiv.
17. For a comprehensive discussion of the law related to orbital debris, see Baker, Howard A., *Space Debris: Legal and Policy Implications*, Martinus Nijhoff Publishers, Boston, 1989.
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3. "Confronting Uncertainty in Risk Management: A Guide for Decision-Makers," Finkel, Adam M., Washington, DC, Resources for the Future, January 1990
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2. Communications Act, as amended, 47 U.S.C. sec. 151, *et seq.*
3. Communications Satellite Act, as amended, 47 U.S.C. sec. 701, *et seq.*
4. Commercial Space Launch Act, as amended, 49 U.S.C. sec. 2601, *et seq.*
5. Land Remote Sensing Commercialization Act, as amended, 15 U.S.C. 4201, *et seq.*
6. National Aeronautics and Space Act, as amended, 42 U.S.C. 250, *et seq.*

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APPENDIX A

AIAA SURVEY OF ORBITAL DEBRIS MITIGATION TECHNIQUES

The following survey is broken into two major categories:

I. Measures taken in the past to mitigate orbital debris generation in design and operation of systems and subsystems of spacecraft each aerospace firm has developed.

II. Potential standards that aerospace firms may propose to further mitigate debris including modifications to hardware, software and operations that will have minimum impact on performance and cost and will improve the overall safety of the system.

Classes of debris are as follows:

1) Spent Upper Stages
2) Satellites and manned spacecraft that have terminated their missions.
3) Pieces of hardware released (deliberately or due to failures) from spacecraft during their missions.
4) Fragments originated from explosions (accidental or induced) and collisions.

Please check mark the appropriate listed measures your firm has taken to mitigate space debris in the past. If your firm plans to implement these measures in the future, place a second check mark next to the first. For possibilities we have omitted, please hand submit those separately with appropriate references to the mitigation technique and class of debris.

Survey Results - Affirmative Response Totals for Each Item

1. Spent Upper Stages

1) Upper stage modifications to design to guarantee reentry or acceleration of decay into atmosphere through:

Measures Taken	Potential Measures	
3	2	Separation maneuver
0	1	Drag devices - deployable sails
0	1	Inflatables

2) Upper stage modifications where reentry is not guaranteed to avoid on orbit explosions:

Measures Taken	Potential Measures	
6	3	Expulsion of excess propellants
5	3	Expulsion of excess pressurants
1	2	Protection of batteries from spontaneous explosion

3) Expendable hardware modifications to reduce excess operational debris to orbit:

Measures Taken	Potential Measures	
2	3	Minimize ELV independent parts allowed to reach orbit
4	5	Secure parts to the upper stages

4) Expendable hardware reduction through operational disposal at low altitude and velocities to reenter such as:

Measures Taken	Potential Measures	
0	3	Separation devices
2	3	Payload shrouds

5) Reduce fuel debris:

Measures Taken	Potential Measures	
0	1	Develop particle free propellants (eliminate aluminum oxide particulates)
Additional inputs:		
1	1	Utilize all liquid propellants

6) Launch Planning:

Measures Taken	Potential Measures	
4	7	Use Collision Avoidance on Launch (COLA) program
0	3	Use Computation of Miss Between Orbits (COMBO) program
0	3	Enhance for accuracy COLA and COMBO programs
1	4	Optimize launch times and dates to exploit natural forces (solar cycle, etc.) to minimize amount of launch debris

2. Satellites and manned spacecraft that have terminated their missions

1) LEO vehicle disposal:

Measures Taken	Potential Measures	
3	5	Deorbit and controlled reentry
0	3	Deployable drag surface
0	2	Inflatables
0	2	Decouple nuclear generators from spacecraft before reentry
1	5	Retrieval and/or reuse of spacecraft

2) High altitude and GEO disposal:

Measures Taken	Potential Measures	
8	5	Orbit maneuvering to shift spacecraft into "graveyard" orbit
0	1	Delta-V to Earth escape velocity
Additional inputs:		
0	1	Use electric propulsion systems to bring spacecraft back to space station for repair, refuel, reconfiguration and reboost

3) Improve debris avoidance:

Measures Taken	Potential Measures	
0	3	Include active "beacon" for spacecraft detection and avoidance
0	2	Passive "reflective" device to ease detection